

**INSTITUTE ON  
■ L A K E ■  
SUPERIOR  
GEOLOGY**

**PROCEEDINGS**

**38TH ANNUAL MEETING  
MAY 6-9, 1992**

**HELD AT**

**HURLEY, WISCONSIN**

**VOLUME 38**

**MAY 1992**

**PART 1  
PROGRAM & ABSTRACTS**

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**ORGANIZING COMMITTEE**  
**38TH ANNUAL MEETING**  
**INSTITUTE ON LAKE SUPERIOR GEOLOGY**

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General Chairman: Albert B. Dickas, University of Wisconsin-Superior  
Program Chairman and Proceedings Editor: Bruce A. Brown,  
Wisconsin Geological and Natural History Survey

Volume 38 consists of  
Part 1: Program and Abstracts  
Part 2: Field Trip Guidebook

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**38TH ANNUAL MEETING**

**MAY 6-9, 1992**

**HURLEY, WISCONSIN**

ORGANIZED BY  
**ALBERT B. DICKAS,**  
UNIVERSITY OF WISCONSIN-SUPERIOR

**BRUCE A. BROWN,**  
WISCONSIN GEOLOGICAL  
AND NATURAL HISTORY SURVEY

**VOLUME 38**

**MAY 1992**

**PART 1**  
**PROGRAM & ABSTRACTS**

## CONTENTS

|                                                        |      |
|--------------------------------------------------------|------|
| Institutes on Lake Superior Geology to 1991            | i    |
| Constitution of the Institute on Lake Superior Geology | ii   |
| By-Laws of the Institute on Lake Superior Geology      | iii  |
| Goldich Medal Guidelines                               | iv   |
| Student Travel Award                                   | v    |
| Board of Directors                                     | vi   |
| Local Committee                                        | vi   |
| Student Paper Award Committee                          | vi   |
| Goldich Medal Committee                                | vi   |
| Goldich Medal Recipient                                | vii  |
| Banquet Speaker                                        | viii |
| Report of the Chair of the 37th Annual Institute       | ix   |
| Calendar of Events and Program                         | xi   |
| Abstracts                                              | 1    |

# INSTITUTES ON LAKE SUPERIOR GEOLOGY

| Institute Number | Date | Place                           |
|------------------|------|---------------------------------|
| 1                | 1955 | Minneapolis, MN                 |
| 2                | 1956 | Houghton, MI                    |
| 3                | 1957 | East Lansing, MI                |
| 4                | 1958 | Duluth, MN                      |
| 5                | 1959 | Minneapolis, MN                 |
| 6                | 1960 | Madison, WI                     |
| 7                | 1961 | Port Arthur, Ont. (Thunder Bay) |
| 8                | 1962 | Houghton, MI                    |
| 9                | 1963 | Duluth, MN                      |
| 10               | 1964 | Ishpeming, MI                   |
| 11               | 1965 | St. Paul, MN                    |
| 12               | 1966 | Sault Ste. Marie, MI            |
| 13               | 1967 | East Lansing, MI                |
| 14               | 1968 | Superior, WI                    |
| 15               | 1969 | Oshkosh, WI                     |
| 16               | 1970 | Thunder Bay, Ont.               |
| 17               | 1971 | Duluth, MN                      |
| 18               | 1972 | Houghton, MI                    |
| 19               | 1973 | Madison, WI                     |
| 20               | 1974 | Sault Ste. Marie, Ont.          |
| 21               | 1975 | Marquette, MI                   |
| 22               | 1976 | St. Paul, MN                    |
| 23               | 1977 | Thunder Bay, Ont.               |
| 24               | 1978 | Milwaukee, WI                   |
| 25               | 1979 | Duluth, MN                      |
| 26               | 1980 | Eau Claire, WI                  |
| 27               | 1981 | East Lansing, MI                |
| 28               | 1982 | International Falls, MN         |
| 29               | 1983 | Houghton, MI                    |
| 30               | 1984 | Wausau, WI                      |
| 31               | 1985 | Kenora, Ont.                    |
| 32               | 1986 | Wisconsin Rapids, WI            |
| 33               | 1987 | Wawa, Ont.                      |
| 34               | 1988 | Marquette, MI                   |
| 35               | 1989 | Duluth, MN                      |
| 36               | 1990 | Thunder Bay, Ont.               |
| 37               | 1991 | Eau Claire, WI                  |
| 38               | 1992 | Hurley, WI                      |

## CONSTITUTION OF INSTITUTE ON LAKE SUPERIOR GEOLOGY

- Article I     Name  
The name of the organization shall be the "Institute on Lake Superior Geology".
- Article II    Objectives  
The objectives of this organization are:
- A. To provide a means whereby geologists in the Great Lakes region may exchange ideas and scientific data.
  - B. To promote better understanding of the geology of the Lake Superior region.
  - C. To plan and conduct geological field trips.
- Article III   Status  
No part of the income of the organization shall inure to the benefit of any member or individual. In the event of dissolution the assets of the organization shall be distributed to \_\_\_\_\_ (some tax free organization).
- (To avoid Federal and State income taxes, the organization should be not only "scientific" or "educational", but also "non-profit".)
- Minn. Stat. Anno. 290.01, subd. 4  
Minn. Stat. Anno. 290.05(9)  
1954 Internal Revenue Code s. 501(c)(3)
- Article IV    Membership  
The membership of the organization shall consist of 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 will be 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 sustained 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  
Glenn Morey  
Greg Mursky

### 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.

## **BOARD OF DIRECTORS**

- 1992 Albert B. Dickas**  
University of Wisconsin-Superior, Superior, Wisconsin 54880
- 1991 P.E. Myers**  
Department of Geology, University of Wisconsin, Eau Claire, Wisconsin  
54701
- 1990 M.M. Kehlenbeck**  
Department of Geology, Lakehead University, Thunder Bay, Ontario P7B 5E1
- 1989 R.W. Ojakangas**  
Department of Geology, University of Minnesota, Duluth, Minnesota 55812

### **Secretary-Treasurer**

M.G. Mudrey, Jr.  
Wisconsin Geological and Natural History Survey  
3817 Mineral Point Road, Madison, Wisconsin 53705

## **LOCAL COMMITTEE**

- A.B. Dickas**  
General Chairman, University of Wisconsin-Superior, Superior, Wisconsin  
54880
- B.A. Brown**  
Proceedings Editor, Wisconsin Geological and Natural History Survey  
3817 Mineral Point Road, Madison, Wisconsin 53705

## **STUDENT PAPER AWARD COMMITTEE 1992**

- Penelope Morton**  
Chairman, Department of Geology, University of Minnesota, Duluth, Minnesota  
55812

## **GOLDICH MEDAL COMMITTEE 1991-92**

- F.W. Cambray (1992)**  
Department of Geological Sciences, Michigan State University, East Lansing,  
Michigan
- H.H. Halls (1993)**  
Department of Geology, Erindall College, Mississauga, Ontario L5L 1C0
- R.D. Sage (1994)**  
Ontario Geological Survey, 777 Grenville Street, Toronto, Ontario, M7A 1W4

## CITATION

W. F. Cannon, Goldich Medal recipient, 1992

W. F. (Bill) Cannon richly deserves this highest honor of the Institute on Lake Superior Geology because of his many outstanding contributions to geology and mineral deposits of the Lake Superior region.

Bill received B.S. and Ph.D. degrees from Syracuse University and in between sandwiched in an M.S. degree from Miami University. He was born, raised, and still remains an easterner at heart, and hence is ideally suited to work in the mostly flat country of the Lake Superior region.

Bill joined the U.S. Geological Survey in 1967. During his early career with the USGS he was mainly a geologic mapper, who slogged through the murky swamps of the Upper Peninsula in his L. L. Bean rubber-soled shoes, and turned out an incredible number of high quality geologic quadrangle maps. These maps will remain as a legacy to his innate ability as a mapper. In addition, he was involved at various times with iron and manganese resource studies on a large scale, and he continues today as an expert on worldwide manganese resources. From 1977 to 1981, he coordinated a successful mineral resource assessment of the Iron River 1°x2° quadrangle, Michigan-Wisconsin.

These glory days in the field terminated in 1981, when he was named Chief of the Branch of Eastern Mineral Resources and then (1984-88) Associate Chief Geologist of the USGS, both of which he served ably. To his credit, while Branch Chief he hired several top-flight, younger geologists, including our colleague Klaus Schulz.

While Associate Chief Geologist, he conceived and master minded a joint U.S.-Canadian deep crustal study (GLIMPCE), in conjunction with Alan Green of the Geological Survey of Canada as well as personnel from numerous state and provincial surveys and universities. This project focused on seismic and potential field investigations of the deep structure of the Midcontinent Rift System, and it has produced more than 50 papers and abstracts. Perhaps this project with its many ramifications is the single most productive scientific achievement carried out in the Lake Superior region in the post-World War II period. It truly brought Keweenaw studies in the Lake Superior region out of the doldrums and into the forefront of science. Bill is author or coauthor of more than 100 reports and maps, several of which concern the rift system.

Bill is a modest, generally quiet guy who never pats himself on the back. Conversations with him, whether about geology (or geophysics) or sports at Syracuse, however, are always lively, and he's a stimulating guy to be with in the field or, after work, in the local bar. He is unique among my close acquaintances in that he drinks a manhattan before dinner, if you know what that is.

I don't know what Bill's middle initial (F.) stands for, but to many of his close associates it stands for a fine, fine fellow.

P. K. Sims

## **BANQUET SPEAKER**

Duff Kerr, Kerr and Associates, Denver, Colorado, will be the speaker at the Annual ILSG Banquet. He will speak on: Industrial petroleum exploration of the Midcontinent Rift Frontier.

## **37TH ANNUAL INSTITUTE ON LAKE SUPERIOR GEOLOGY EAU CLAIRE, WISCONSIN, 1991**

The 37th Annual Meeting of the Institute on Lake Superior Geology met from May 1-4, 1991 in Eau Claire, Wisconsin. The host for this meeting was the University of Wisconsin-Eau Claire. Paul E. Myers was the General Chairman. Lung S. Chan coordinated publications and field trips. The Proceedings of this conference were published in two parts: Part I contains the abstracts, and Part II contains field guides for the three conference field trips.

Technical sessions and banquet were held in the Civic Center Inn, Eau Claire. A total of 154 geologists from the Lake Superior region registered, and 92 people attended the annual banquet. The technical sessions included 31 oral papers and 23 poster papers. A symposium on the mineral resources potential of northern Wisconsin comprised eight papers by geologists from the mining industry and Wisconsin Geological and Natural History Survey.

A pre-conference field trip (#1), led by Paul K. Sims and John S. Klasner, studied "The Mountain shear zone—a post-Penokean discrete ductile deformation zone." The guidebook for this field trip was authored by P.K. Sims, J.S. Klasner, W.C. Day, and Z.E. Peterman.

A second pre-conference field trip (#2) concentrated on the "Features and significance of the Precambrian-Cambrian contact in western Wisconsin." The trip, including stops near Eau Claire, Black River Falls, and Neillsville, Wisconsin, was led by Lung S. Chan and Richard L. Hay, with additional field guide materials by Paul E. Myers.

A post-conference field trip, entitled "Proterozoic volcanogenic massive sulfide deposits of Northwestern Wisconsin," involved mainly the inspection of cores from the Flambeau, Lynne, and Bend deposits at Ladysmith and Hawkins, Wisconsin. Co-leaders for this trip were M.G. Mudrey, Jr., and B.A. Brown, both of the Wisconsin Geological and Natural History Survey.

A total of 87 people attended these three field trips. Vans for the pre-conference field trips were driven by undergraduate geology students Mike Squire, Tony Jones, Zach Kostalek, and Michelle Barnes from the University of Wisconsin-Eau Claire.

The Annual Banquet on May 2 was attended by 92 people. Val W. Chandler, Minnesota Geological Survey, presented the 1991 Goldich Medal to William J. Hinze, Purdue University, for his many contributions as an educator and in geophysical studies of the Great Lakes region. The Goldich Award Committee included M.G. Mudrey, Jr., H.H. Halls, and F.W. Cambray. The Annual Banquet speaker was Paul K. Sims. His topic was, "Archean and Early Proterozoic Geology of the Lake Superior Region—an Overview."

Students travel awards totalling \$1080 were presented to five students giving papers: Sidney Hemming, Matt Manson, James Johnson, Denise Stavish, and Mary Tozer. Three \$150 awards for best oral and poster papers went to 3 students: David J. Allen, John Mariano, and Michael D. Thompson. John Klasner, John Gardener, and William Cannon served on the Best Student Paper Award Committee.

The I.L.S.G. Board of Directors met in Eau Claire on May 2. The meeting was attended by M.G. Mudrey, Jr., M.M. Kehlenbeck, P.E. Myers, L.S. Chan, J. Klasner, R.W. Ojakangas, and A.B. Dickas.

The following items were discussed:

- (1) The site for the 1992 meeting will be at Hurley, Wisconsin, on May 6-9. Co-hosts for this conference are A.B. Dickas of University of Wisconsin-Superior and B.A. Brown of Wisconsin Geological and Natural History Survey.

(2) Treasurer's Report:

Michigan account was transferred to Wisconsin with Bruce Brown having a full power of attorney with M.G. Mudrey, Jr. \$1000 was placed in ready checking account and remainder (about \$4000) was placed in a CD (Mt. Horeb). The Goldich account was placed in a three-year CD, the rest in 6-month CDs total about \$6800.

Mudrey has old field trip guidebooks; proceedings are still at Houghton Tech.

Glen Morey still has old Goldich medals. Their present value is approximately \$200. In 1988 there were 12 medals, then valued at \$115 = \$1380.

(3) Procedures for limited student travel assistance awards:

A motion was made (M.K.) to develop a form for itemizing anticipated costs for travel and lodging with total awards not exceeding \$1000 (shared equally by Canadian and U.S. treasuries) and individual awards of no more than \$200. This motion was not voted on.

Another motion was made (J.K.) to provide assistance to faculty in bringing students to institutes to a maximum of \$50. The motion was amended to recommend that partial or total remission of fees may, at the discretion of the local committee, be used as an incentive for attracting students. The motion passed.

Lung Chan and I wish to thank those who generously donated time and talents to make the 1991 meeting a success.

Respectfully submitted,

P.E. Myers

General Chairman, I.L.S.G., 1991

## CALENDAR OF EVENTS AND PROGRAM

### Wednesday, May 6

**Field Trip 1 Early Proterozoic and Archean rock of the Gogebic Range.**

Leaders: G.L. LaBerge, R.W. Ojakangas, and K. Licht

8:00 am Registration and departure, Holiday Inn lobby

6:30 pm Return

**Field Trip 2 Evolution of the Keweenawan sedimentary sequence.**

Leaders: M.G. Mudrey, Jr., and A.B. Dickas

8:00 am Registration and departure, Holiday Inn lobby

6:30 pm Return

4:00–8:00 pm Registration and check-in, Holiday Inn lobby

7:00–11:00 pm **Icebreaker** (cash bar)/Poster session, Holiday Inn Conference Room

### Thursday, May 7

*All technical sessions and poster sessions are in the Conference Room at the Hurley, Wisconsin, Holiday Inn. Contributors should have posters up by noon, Thursday, May 7.*

7:15 am Registration, Holiday Inn lobby

**Archean Session: Frank Luther, session chair (8:30–9:50 am)**

8:30 am Theodore J. Bornhorst, Richard T. Wilkin, and Rodney C. Johnson

*Temporal progression of Archean granitoid rocks,  
Ishpeming greenstone belt and vicinity, Michigan*

8:50 am A.C. Turnock and D.C. Kamineni

*Thermal and regional metamorphism in Archean basalt,  
Bird River Greenstone Belt, Manitoba, Canada*

9:10 am Barbara E. Seemayer and Manfred M. Kehlenbeck

*Variations in metamorphic grade of metapelites along transects  
across the Quetico Subprovince*

9:30 am Terrence J. Boerboom and Mark A. Jirsa

*Geology and tectonic setting of the Archean Giants Range Batholith;  
Western Wawa Subprovince, Minnesota*

9:50 am **Coffee break**

**Geophysics Session: C. Patrick Ervin, session chair (10:10–11:50 am)**

- 10:10 am Daniel J. Brehm, C. Patrick Ervin, and Jeffrey K. Greenberg  
*Gravity model of the Wolf River Batholith*
- 10:30 am Lung S. Chan, Zachary Kostalek, and Richard L. Hay  
*Isotope and paleomagnetic dating of weathered granite below the Precambrian-Cambrian contact in Neillsville, Wisconsin*
- 10:50 am Stephen A. Kissin, Graham J. Borradaile, Joe D. Stewart, William A. Ross, and Thomasz Werner  
*Magnetic and petrographic detection of heat treatment in Gunflint Chert*
- 11:10 am Timothy B. Holst and Haakon Fossen  
*On the use of paleocurrent indicators in deformed rock*
- 11:30 am Michelle L. Barnes, Georgia L. Osborn, and Lung S. Chan  
*An integrated gravity and magnetic survey of the Rock Elm structure, western Wisconsin*
- 11:50 am **Lunch break**  
Institute on Lake Superior Geology Board of Directors Luncheon (by invitation)  
Posters on display

**Proterozoic Session I: Richard W. Ojakangas, session chair (2:00–3:20 pm)**

- 2:00 pm Gene L. LaBerge  
*The Early Proterozoic Emperor volcanic complex: Implications for the geology of the eastern Gogebic District, northern Michigan*
- 2:20 pm Kathy Licht and T.P. Flood  
*The chemistry and petrography of mafic rocks from the Early Proterozoic Emperor volcanic complex near Marinesco, Michigan*
- 2:40 pm S.R. Hemming, S.M. McLennan, and G.N. Hanson  
*Provenance of the Animikie Group, NE Minnesota, based on Nd and Pb isotopes*
- 3:00 pm Mark E. Davidson and John C. Palmquist  
*Implications of strain and magnetic anisotropy studies for the Penokean Orogeny, Upper Michigan*
- 3:20 pm **Coffee break**

**Proterozoic Session II: Bruce A. Brown, session chair (3:40–4:40 pm)**

3:40 pm Richard W. Ojakangas and Jukka S. Marmo  
*Early Proterozoic leptite & halleflinta (tuff & tuffite) sequences of southern Finland reinterpreted as shear zones: Significance to Lake Superior geology*

4:00 pm M.G. Mudrey, Jr., and B.A. Brown  
*Penokean structural trends defined from formational contacts and cleavage analysis along the Gogebic Range, Wisconsin*

4:20 pm Xinping Yin and James A. Grant  
*Geochemistry of the metadiabases in the Republic Mine area, northern Michigan*

4:40 pm End of technical sessions for the day  
Posters on display

6:00–7:00 pm **Mixer, cash bar**

7:00–10:00pm **Annual Banquet**

Announcement of 39th Annual Meeting location, 1993.

Goldich Award presentation to William F. Cannon by Paul K. Sims.

Banquet speaker: Duff Kerr, Kerr and Associates, Denver, Colorado;

*Industrial Petroleum Exploration of the Midcontinent Rift Frontier*

**Friday, May 8**

8:00 am Registration, Holiday Inn lobby

**Midcontinent Tectonics and Processes Session I: William J. Hinze, session chair (8:30–10:00 am)**

8:30 am William F. Cannon  
*Process rates during Midcontinent rifting:  
Clues to the origin of the Midcontinent Rift System*

8:55 am J.D. Miller, Jr.  
*The need for a new paradigm regarding the petrogenesis of the Duluth Complex*

9:20 am Albert B. Dickas  
*Preliminary report, geology and geophysics of the Terra/Patrick #7-22 wildcat hydrocarbon test, Midcontinent Rift, Keystone Township, Bayfield County, Wisconsin*

9:40 am David J. Allen and Val W. Chandler  
*The utility of high-resolution aeromagnetic data for investigating the  
Midcontinent Rift in east-central Minnesota*

10:00 am **Coffee break**

**Midcontinent Tectonics and Processes Session II: A.B. Dickas, session chair**  
(10:20–11:20 am)

10:20 am Pieter Berendsen  
*Structure and composition of Keweenawan rift-related igneous and  
sedimentary rocks in Kansas*

10:40 am Kathleen M. Witthuhn  
*A structural analysis of the Midcontinent Rift in Michigan,  
based on a fault array analysis utilizing slickensides*

11:00 am John C. Green  
*The Palisade Rhyolite, Lake County, Minnesota:  
A cryptic rheoignimbrite in the North Shore Volcanics*

11:20 am **Lunch break**  
Posters on display

**Economic Geology Session I: Lawrence Kennedy, session chair (1:00–2:20 pm)**

1:00 pm Anthony J. Deevy  
*Magino, the making of a mine*

1:20 pm Susan E. Brink  
*Textural and compositional study of a managaniferous iron-formation,  
Emily District, Cuyuna Range, with implications for original deposition  
and in situ leaching of manganese*

1:40 pm G.B. Morey, Peter L. McSwiggen, and Jane M. Cleland  
*Evidence of an exhalative contribution to the manganese mineralogy of  
the Trommald Formation, Cuyuna Iron Range, east-central Minnesota*

2:00 pm Susan E. Brink  
*The petrology and geochemistry of the Spirit volcanogenic massive  
sulfide prospect, north-central Wisconsin*

2:20 pm **Coffee break**  
Presentation of student awards

**Economic Geology Session II: Allan M. Johnson, session chair (2:40–3:40 pm)**

- 2:40 pm Penelope Morton and Stephen D. Geerts  
*High temperature hydrothermal alteration associated with  
PGE enrichment of Cu-Ni sulfides, Dunka Road, Duluth Complex,  
NE Minnesota*
- 3:00 pm Mark J. Severson  
*Sulfide and PGE mineralization at the basal contact of the  
Minnamox deposit, Duluth Complex, NE Minnesota*
- 3:20 pm Daniel N. Miller, Jr.  
*Accessing the Anaconda Geological Documents Collection  
Minnesota - Wisconsin - Michigan - Ontario*
- 3:40 pm **End of technical sessions**
- 5:00 pm **Field Trip 4 departure for Marquette**

**Saturday, May 9**

**Field Trip 3 Geology of Keweenaw rock near the Porcupine Mountains,  
Ontonagon and Gogebic Counties, Michigan.**

Leaders: W.F. Cannon, S.S. Nicholson, C. Hedgman,  
L. Woodruff, and K.J. Schulz

8:00 am Departure from Holiday Inn, Hurley

4:30 pm Return

**Field Trip 4 Geology of the Great Lakes tectonic zone in the Marquette area,  
Michigan—A late Archean paleosuture.**

Leader: P.K. Sims and Z.E. Peterman

8:00 am (Eastern Daylight Savings)—Departure from Ramada Inn, Marquette, Michigan

4:30 pm (Eastern Daylight Savings)—End of trip

6:00 pm (Central Daylight Savings)—Return to Hurley

## POSTER PRESENTATIONS

### Archean

Frank R. Luther

*Magnetite octahedra in pillow basalt near Wawa, Ontario*

### Geophysics

C. Patrick Ervin, M.G. Mudrey, Jr., B.A. Brown, and M.L. Czechanski  
*1991 COGEOMAP gravity mapping program in west-central Wisconsin:  
The Driftless Area*

### Proterozoic

Bradley Hellickson, Stanley Radzevicius, and Garry Anderson  
*Petrology and structure of a rapakivi body from east-central Minnesota*

Daniel Holm, Timothy Holst, and Daniel Lux  
*Thermochronologic evidence for post-Penokean unroofing  
in the Lake Superior region*

G.B. Morey and Terrence J. Boerboom  
*Rare earth element distribution patterns in Early Proterozoic iron  
formations of the Penokean orogen, east-central Minnesota*

Andrew D. Moshoian, Karl R. Wirth, and John P. Craddock  
*The Kenora-Kabetogama dike swarm: Results of trace element studies*

### Midcontinent tectonics and processes

Albert B. Dickas and M.G. Mudrey, Jr.  
*Precambrian hydrocarbon potential of the western Great Lakes*

Cheryl A. Hedgman  
*Petrology and provenance of a conglomerate facies of the  
Jacobsville Sandstone: Iron to Bergland, Michigan*

R.J. Horton, R.J. Bisdorf, and R.P. Kucks  
*Airborne geophysical survey of northwestern Wisconsin*

William F. Kean and John Feeney  
*Magnetic studies of the Dresser-St. Croix Falls area, Polk County, Wisconsin*

S.D. McDowell, K.L. Price, J. Huntoon, and T.J. Bornhorst  
*Thermal modeling and illite/smectite geothermometry of the  
Precambrian Oronto Group, Wisconsin and Michigan*

## Economic geology

P. Hinz and R.T. Lucas

*Exploration and mining activities of industrial minerals in northwestern Ontario*

Stephen A. Kissin, Peter G. Harvey, Elizabeth A. Jennings, Samuel T. Spivak,  
and Eric J. Mosley

*Alteration, fluid inclusion, stable isotopic and structural studies of the  
Rabbit Mountain Silver Mine, Thunder Bay District, Ontario*

Peter L. McSwiggen, G.B. Morey, and Jane M. Cleland

*Acmite in the Trommald Formation of the Cuyuna Iron Range: Revisited*

M.G. Mudrey, Jr., and A.B. Dickas

*Geologic setting of the Early Proterozoic metal-rich volcanics of the  
upper Great Lakes region*

Richard Patelke and Mark Severson

*Petrology and origin of the northern Colvin Creek Body,  
Duluth Complex, NE Minnesota*

# ABSTRACTS

# **The Utility of High-Resolution Aeromagnetic Data for Investigating the Midcontinent Rift in East-Central Minnesota**

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## **Introduction**

Aeromagnetic data are useful for delineating the structure of the Midcontinent Rift System (MCR). Along the western arm of the MCR, magnetic anomalies have been used to map buried Keweenawan volcanic and sedimentary rocks and to identify major structures, including basins and faults (e.g., Sims and Zietz, 1967; King and Zietz, 1971). In 1991, the Minnesota Geological Survey (MGS) completed a high-resolution aeromagnetic survey of Minnesota (Chandler, 1991). Nearly all of the state was surveyed with a terrain clearance of 150-200 meters and a flight line separation of 400-500 meters. This statewide aeromagnetic database, the only one in North America encompassing a large region with high resolution, provides a new opportunity to examine the western arm of the MCR in detail.

A 213 meter data grid was generated from the aeromagnetic survey. This data set contains detailed information about the Precambrian basement of Minnesota and provides excellent images of the MCR, including the Duluth Complex and North Shore Volcanic Group, a large portion of the St. Croix Horst, the Belle Plaine Fault, and the extreme northern tip of the Iowa Horst. To take full advantage of these data, new methods of display are presently being developed, including stereoscopic data presentation and improved shaded relief techniques.

## **Preliminary Results**

The present study focuses on the St. Croix Horst (SCH). Figure 1 is a magnetic map of east-central Minnesota and adjacent Wisconsin. The MGS 213 m data grid was merged with data from an older USGS survey in extreme western Wisconsin (Sims and Zietz, 1967) and data from the DNAG 2 km magnetic grid, based on a survey by Patenaude (1966), for the remainder of Wisconsin. In addition, the Twin Cities metropolitan region was not included in the high-resolution aeromagnetic survey; in this area, the MGS 213 m grid is based on data acquired by the USGS in 1961. The specifications for each survey are listed in Table 1. As shown in Figure 1, the new high-resolution data clearly portray features which are poorly resolved by the older USGS surveys and completely absent in the DNAG 2 km data grid.

Figure 2 is an interpretive map of the MCR based on the aeromagnetic data. Areas underlain by (essentially non-magnetic) Keweenawan sedimentary rocks are characterized by subdued magnetic patterns, whereas (magnetic) Keweenawan volcanic rocks are often associated with narrow linear anomalies, many of which are continuous for over 50 km along strike. Where the rift rocks crop out, they strike parallel to the trends of the magnetic anomalies. This correlation is useful for mapping volcanic packages and delineating folds within the SCH. In addition, abrupt terminations of the linear anomalies are useful for identifying faults.

Several northeast-trending anomalies are produced by Keweenawan dikes. These dikes lie west of the MCR and strike parallel to the rift axis (Figs. 1-2). Within the SCH, lineaments cut across the magnetic anomalies associated with the volcanic rocks. The lineaments do not truncate or significantly offset the magnetic

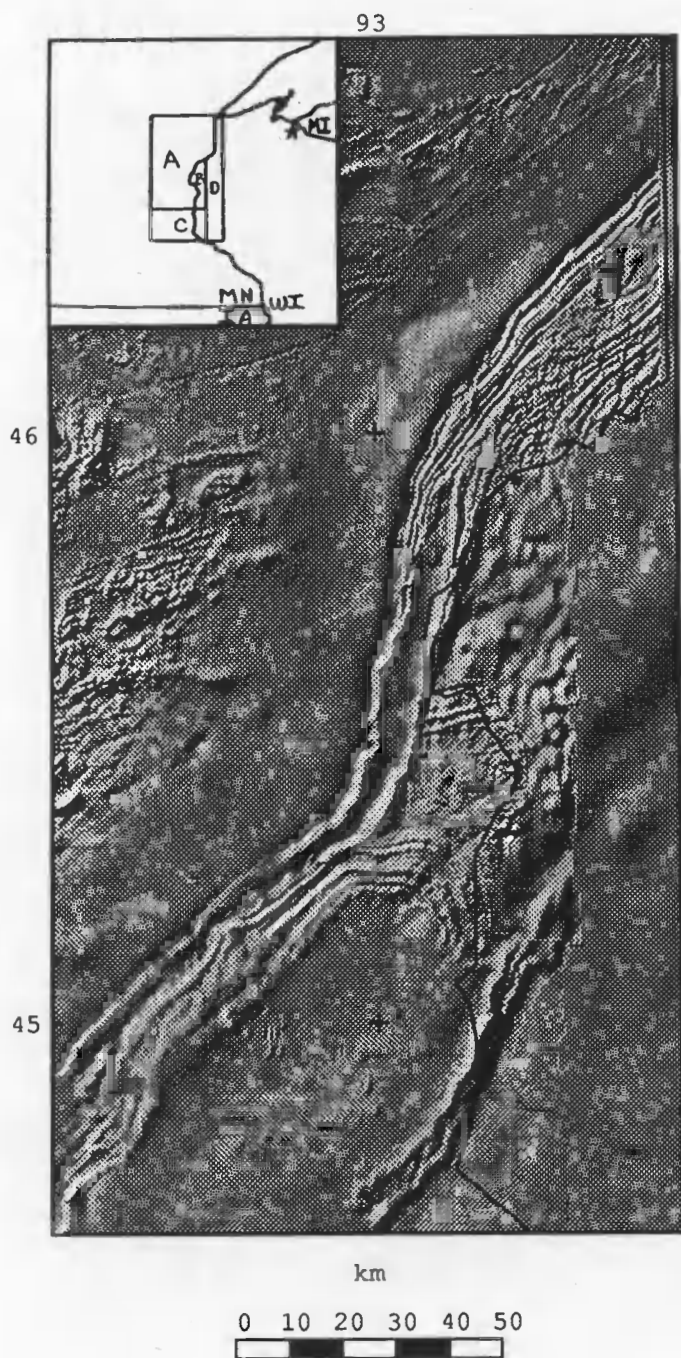


Figure 1: Shaded relief presentation of magnetic data for east-central MN and adjacent WI. The sun illumination is from the northwest.

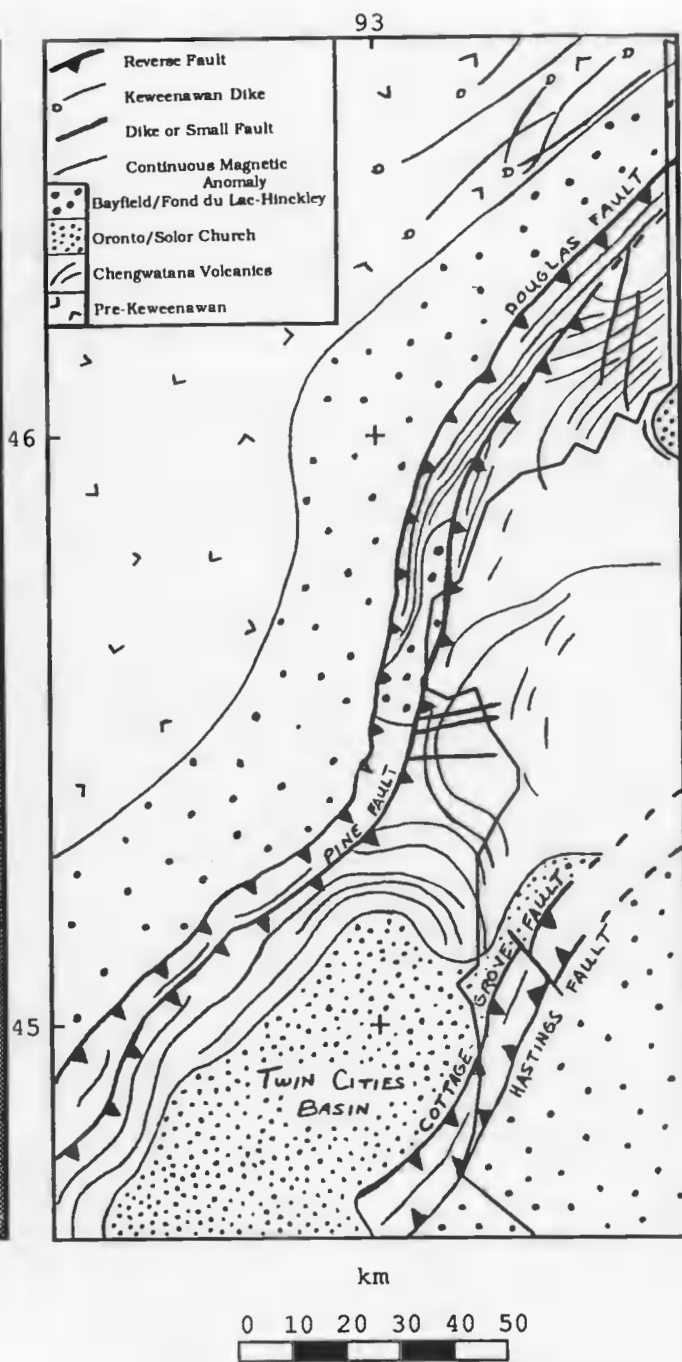


Figure 2: Interpretive map of the MCR based on aeromagnetic data.

Table 1: Aeromagnetic Survey Specifications (see Figure 1)

| Survey                 | Elevation                       | Flight line separation and direction |             |
|------------------------|---------------------------------|--------------------------------------|-------------|
| A MGS, 1991            | 200 m above ground              | 500 m                                | North-South |
| B Sims and Zietz, 1967 | 500 ft (150 m) above ground     | 1 mile (1600 m)                      | East-West   |
| C USGS, 1961           | 500 ft (150 m) above ground     | 1 mile (1600 m)                      | East-West   |
| D Patenaude, 1966      | 3000 ft (900 m) above sea level | 6 miles (9600 m)                     | North-South |

anomalies, suggesting that they might be produced by dikes, faults of minimal displacement, or fracture zones within which the magnetic character of the volcanic rocks was altered.

The most prominent magnetic anomalies are associated with reverse faults along the margins of the SCH which juxtapose volcanic and sedimentary rocks. Of particular interest is the Pine Fault. North of the Pre-Paleozoic Twin Cities Basin, this fault places older volcanic rocks to the east in contact with younger sedimentary rocks to the west. The new magnetic data indicate that the Pine Fault continues northeast beyond 46°N, to within 20 km of the Minnesota-Wisconsin border (Figs. 1-2).

### Additional Problems

Thus far, the high-resolution magnetic data have been used in a qualitative manner to interpret the structure of the SCH. Continued efforts to enhance the display of this data set will hopefully result in improved images of the SCH and better resolution of the structural complexities within the rift's volcanic rocks.

Magnetic modeling will be a powerful tool for quantifying interpretations of the SCH. A major objective will be to determine the sources of the continuous linear magnetic anomalies associated with the rift's volcanic rocks. These anomalies might be produced by contrasts between volcanic flows and interflow sedimentary units, differences in magnetic properties between adjacent packages of volcanic rocks, or magnetic reversals. These hypotheses will be evaluated using magnetic modeling in conjunction with magnetic properties measurements of volcanic rocks from the SCH.

Magnetic modeling will also be useful for investigating the longer wavelength anomalies (not evident in the shaded relief presentation of Figure 1). Analytical techniques which account for structural rotation of the remanent magnetization vector (e.g., Mariano and Hinze, 1991), in conjunction with available seismic reflection data and gravity modeling, will lead to more reliable models of the deeper structure of the SCH.

The MGS data set also provides an opportunity to examine other portions of the MCR. For example, these data may lead to an improved understanding of the transition between the St. Croix and Iowa Horsts along the Belle Plaine Fault in southeastern Minnesota. In addition, the data may also assist in improving interpretations of the Duluth Complex and North Shore Volcanic Group. Finally, the detail provided by the MGS survey suggests that a similar high-resolution survey of northwestern Wisconsin might be extremely useful for investigating the nature of the transition between the western arm of the MCR and the Lake Superior Basin.

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# AN INTEGRATED GRAVITY AND MAGNETIC SURVEY OF THE ROCK ELM STRUCTURE, WESTERN WISCONSIN

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The Rock Elm structure, located in Pierce County, Wisconsin, is an approximately four miles in diameter, sub-circular structure of uncertain origin. The structure contains Paleozoic strata tilted away from a central dome where brecciated rocks are present. Several hypotheses for the origin of the structure have been suggested: 1) meteorite impact (Cordua, 1985), 2) volcanic activity, and 3) tectonic activity. Of the three, we looked most closely at the first one and have conducted an integrated gravimetric and magnetic survey to determine the plausibility of this hypothesis.

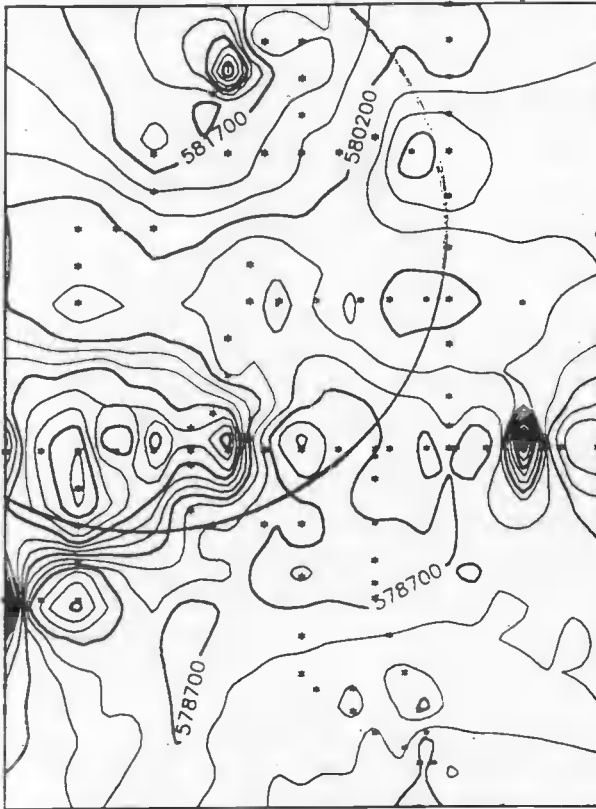
Gravity measurements were taken using a LaCoste & Romberg gravity meter at one mile intervals, mostly at USGS elevation markers, over an area 12 miles x 14 miles. Free-air and Bouguer corrections were applied to all measurements and terrain corrections were applied where needed. A proton precession magnetometer was used to measure the ambient magnetic field and the vertical gradient of the field intensity in and around the structure. Multiple measurements were taken at stations positioned about every quarter mile along the grid pattern created by the roads in the area.

We have compared our gravity and magnetic results (Figures 1 and 2) to those of the Manson Impact Structure in Iowa, which has strong magnetic anomalies associated with its boundary (Hartung and Anderson, 1988). The Rock Elm structure does not show significant magnetic anomalies along its boundary nor with its central dome. The gravity data also do not support the hypothesis of an impact origin. A northwest-southeast trend in the gravity anomaly coincides with the River Falls anticline and the Lake Owen Thrust Fault of the Mid-Continent Rift System. We have also computed gravity and magnetic anomalies of hypothetical impact structures constructed from known geological constraints. The simulated models do not resemble the geophysical results observed.

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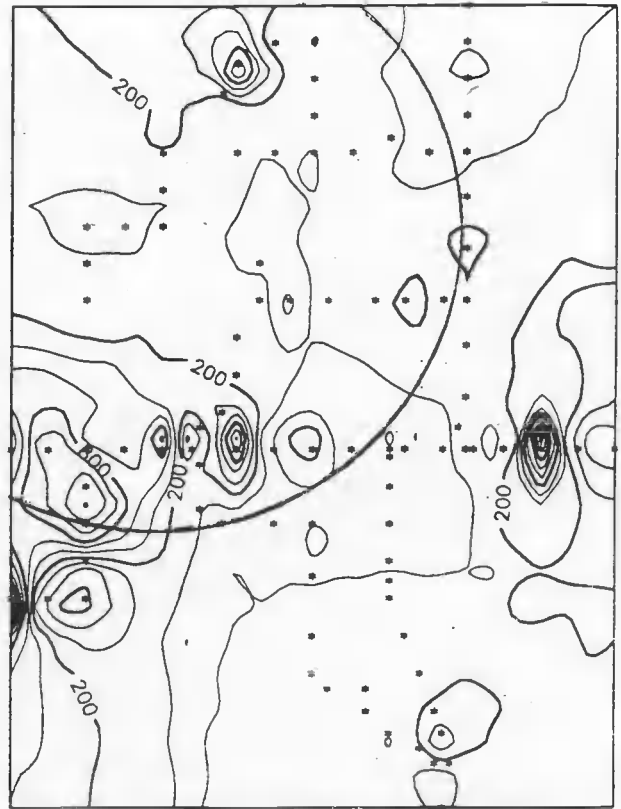
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# ROCK ELM, TOP SENSOR



Contour Interval, 500nT

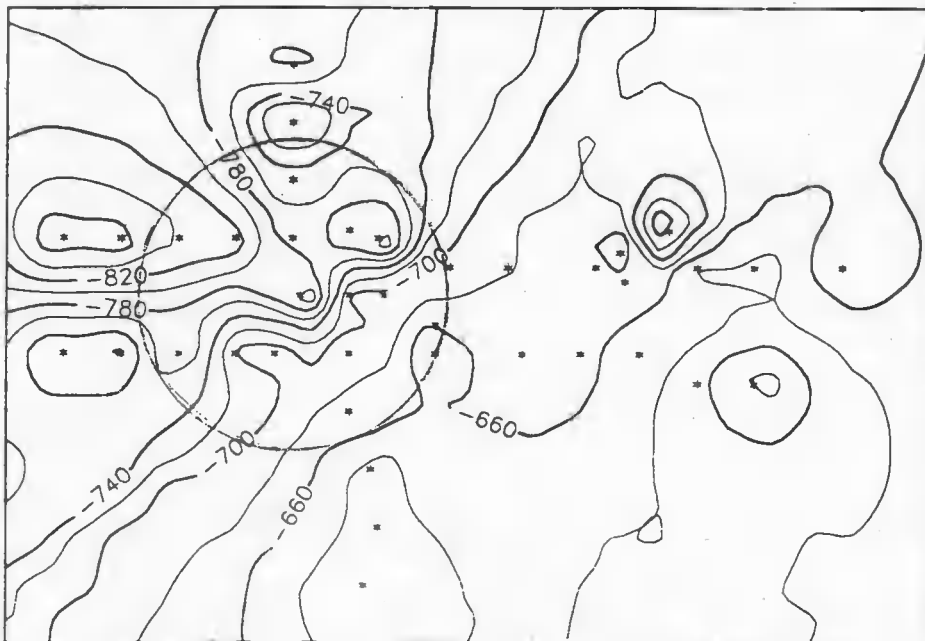
# ROCK ELM, GRADIENT



Contour Interval, 200nT

Figure 1. Magnetic anomalies of the Rock Elm area. The circle represents the approximate boundary of the structure.

# GRAVITY ANOMALY AT ROCK ELM



Contour Interval, 20gu

Figure 2. Gravity anomaly of the Rock Elm area. The circle represents the approximate boundary of the structure.

# **Structure and composition of Keweenawan rift-related igneous and sedimentary rocks in Kansas.**

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During the last decade a series of holes were drilled into the Precambrian basement. Prominent among these are the Noel Poersch #1, which is the deepest drill hole to date in Kansas at 11,300 feet, and two OZ drill holes, which are in close proximity to the Poersch hole. These three wells were drilled in 1984-85 by Texaco in Washington County, northeastern Kansas (Figure 1). The Finn #1-4 and the Friederich #1-8 in Marshall and Riley counties respectively, are two other wells with significant penetrations into the Proterozoic basement (Figure 1). Studies of well cuttings and some core from these and older drill holes generated a lot of new data and made it possible to better interpret the nature of rift.

Comparative petrographic studies of representative outcrop samples from the Lake Superior region and subsurface samples from Kansas were conducted. The mineralogical composition and the heavy mineral content of core and cuttings allow comparison and general stratigraphic correlations with rocks from the outcrop belt in the Lake Superior area. The amount of quartz, plagioclase and K-feldspar, the amount and nature of rock fragments, the tourmaline, zircon, and epidote content are all discriminating factors.

Chemical analysis of the basalts and gabbros encountered in the four drill holes in northeastern Kansas shows them to be alkalic to subalkalic (Figure 2). Baddeleyite from gabbro in the upper portion of the Poersch drill hole yields a concordant U-Pb age of 1097.5  $\pm$  3 Ma (Van Schmus and others, 1990). This is essentially the same age as published data for the Lake Superior region, and indicates that no age progression took place along this arm of the rift. The lower 3874 feet in the Poersch drill hole penetrated a predominantly arkosic section from which detrital monazite and zircon were recovered. U-Pb provenance ages of these minerals range from 1.7-1.8 Ga, 1.4-1.5 Ga, and 1.1-1.2 Ga (Martin, Personal Communication). From this it appears that most of the arkosic sedimentary rocks were derived proximally from the adjacent rift margins, which consist of 1.7-1.8 Ga mostly granitic basement and younger (1.45 Ga) granitic plutons. No evidence of early Proterozoic or Archaean detrital minerals was found, indicating that transport of sedimentary materials along the axis of the rift from farther up north may not have been significant.

Core taken from gabbro of the OZ drill hole has stable magnetic remanence which demagnetizes from shallow, reverse to steep, reverse inclination and appears to date from original cooling (Van Schmus and others, 1990). This may be correlated with Lower Keweenawan rocks that occur below the R to N magnetic reversal.

In the Poersch drill hole a predominantly volcanic section, approximately 4580 foot thick overlies the mostly arkosic sedimentary rock section. Based on seismic evidence from a COCORP line four miles north of the Poersch drill hole, Woelk and Hinze (1991) propose that a high-angle, west-dipping, reverse fault is responsible for the transposed order of the major rock packages. This fault has an approximate strike of N 40°E, and dips steeply to the west. Examination of the seismic profile shows that a

steeply east-dipping reverse fault, having a strike of N40<sup>0</sup>E, could also be responsible for the transposition.

North-northeast- and northwest-trending faults dominate the structures associated with the rift in Kansas. Presently, a pattern of roughly rectangular structural blocks, each having a narrow range of elevations above sea level, gives a characteristic appearance. Apparent compound vertical offset on faults can be as much as 2000 feet. Within the Paleozoic era repeated reactivation of earlier tectonic trends can be documented. The magnitude and number of times to which rift-related rocks were subjected to faulting in the Proterozoic is unknown. The last major adjustment on faults occurred during the Pennsylvanian Ouachita orogeny. Preliminary studies in Kansas indicate that sedimentary and igneous suites of rocks of widely differing ages may be juxtaposed in adjoining structural blocks.

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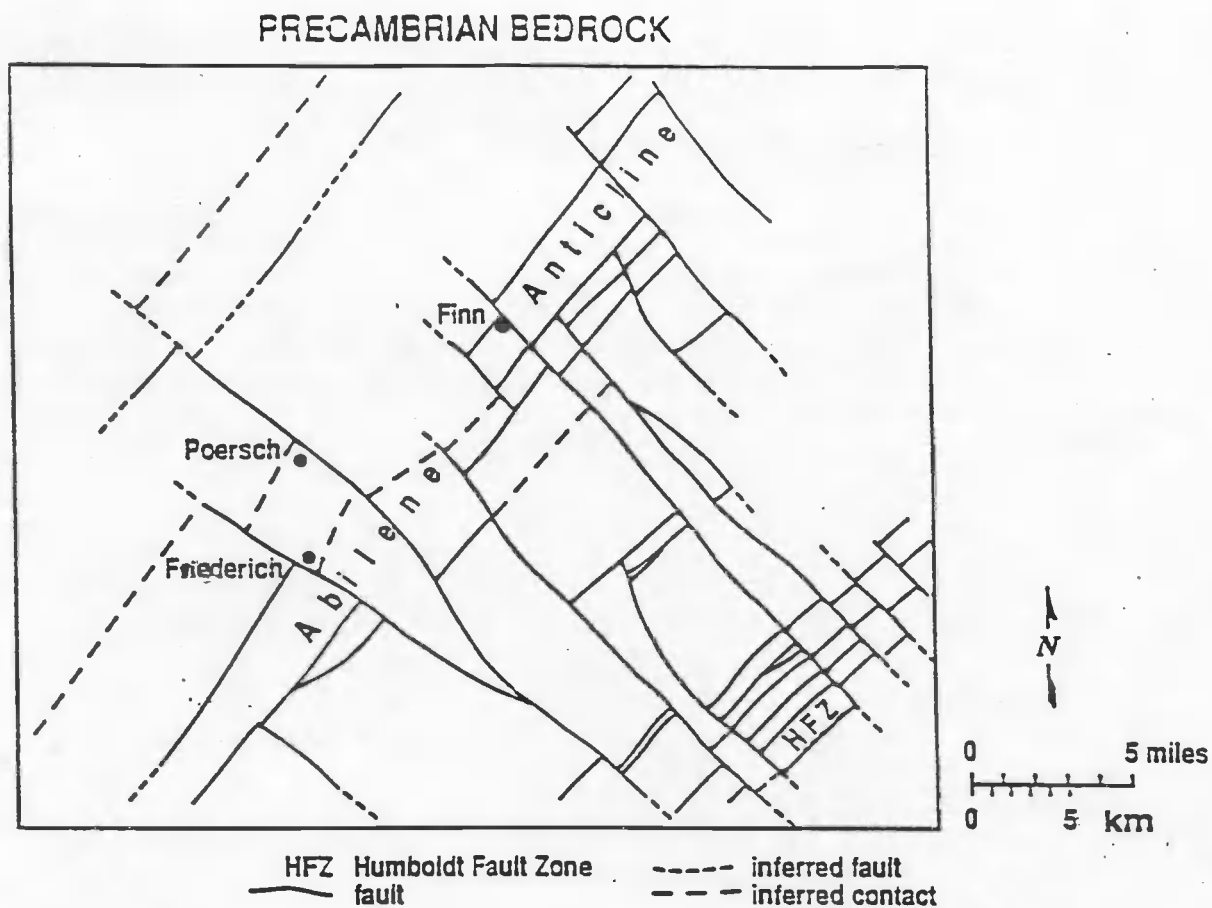


Figure 1. Basement structure in the vicinity of the Finn, Poersch and Friedrich drill holes, north-central Kansas.

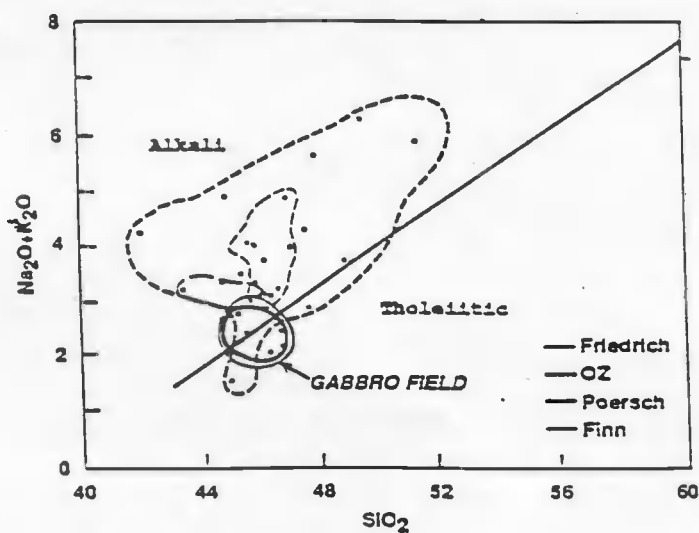


Figure 2 Alkalies vs  $\text{SiO}_2$  diagram showing Keweenaw lavas and gabbros.

# GEOLOGY AND TECTONIC SETTING OF THE ARCHEAN GIANTS RANGE BATHOLITH; WESTERN WAWA SUBPROVINCE, MINNESOTA

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The Giants Range batholith (GRB) is a large composite granitoid body of Late Archean age that intrudes supracrustal rocks of the Wawa subprovince. It is truncated by the Proterozoic Duluth Complex at its east end, and extends westward for more than 200 km to north-central Minnesota, where it is deeply buried beneath Quaternary sediment. This study is based on detailed outcrop mapping, and to a lesser extent on drill core and geophysical data in the westernmost exposed part of the batholith and several satellite plutons. The GRB intrudes complexly deformed metavolcanic and metasedimentary rocks of the Lake Vermilion Formation. Two main periods of deformation have been identified in the supracrustal rocks: a D1 event that produced large scale, locally recumbent folds but only a rarely preserved cleavage; and a D2 that produced NE-trending, upright folds and associated, steep axial planar cleavage. Mineral lineations and foliations that parallel F2 fold axes indicate that peak metamorphism (M2), which varies from greenschist to amphibolite facies, occurred during D2. Field relationships show that some portions of the GRB are older than D2 and the associated M2 metamorphism, and others are younger. Localized structures that were generated after M2 and after plutonism are assigned to D3.

The GRB exposed in the study area consists of earlier, pre- to syn-D2, lineated and hornblende-bearing granodiorite and monzodiorite, and later, muscovite- and biotite-bearing granite which was only slightly affected by D2 deformation. Several smaller, ovoid plutons of petrochemically diverse alkalic affinity were emplaced after peak metamorphism into supracrustal rocks adjacent to the GRB. The best exposed example of the earlier suite of rocks is the Britt granodiorite which occurs in and near a large antiform in the south part of the map area. The rock is metaluminous and I-type. The proportions of Rb, Y, Yb, Nb and Ta in the Britt granodiorite imply that it was emplaced in a volcanic arc. This tectonic inference also is supported by major element data and discrimination plots. The granodiorite is intruded by the Shannon Lake granite, a weakly to moderately foliated, multiphase, biotite-muscovite granite. Emplacement of the Shannon Lake granite clearly post-dates M2 in the area. However, weak NE-trending fabrics cross the trend of magmatically related pegmatite and aplite dikes that occur both in the granite and in the adjacent supracrustal rocks. Thus, some regional deformation occurred after intrusion. Geochemical discrimination diagrams for the Shannon Lake granite place it between the island-arc and continental-collision classes of granitoids. Some plutons of alkalic rocks (such as the Idington pluton) are intruded by Shannon Lake granite, and therefore are somewhat older than the Shannon Lake. However, the alkalic plutons and the Shannon Lake are both post-tectonic with respect to D2, and may be broadly contemporaneous.

The Britt granodiorite and the Shannon Lake granite were emplaced before and after the main D2 deformation, respectively. D2 is a transpressive deformational event of wide regional extent that can be generally correlated across the southern Superior Province. High-precision U-Pb dating has been done on zircons from these two rock units, and the preliminary results indicate that D2 ended between 2674 and 2685 Ma (R. Zartman, U.S. Geological Survey, pers. communication). A full report of the geochronologic work will be published soon.

This project was supported in part by the Mineral Diversification Program administered by the Minerals Coordinating Committee for the Minnesota State Legislature.

**TEMPORAL PROGRESSION OF ARCHEAN GRANITOID ROCKS,  
ISHPEMING GREENSTONE BELT AND VICINITY, MICHIGAN**

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Granitoid rocks can now be integrated into the volcanic rock unit and structural framework of the Ishpeming greenstone belt and the development of the Great Lakes tectonic zone (GLTZ; Sims, 1991). The Ishpeming greenstone belt is composed of more than 13,000 meters of mafic and felsic volcanic rocks erupted during active north-directed subduction about 2700 Ma. These volcanic rocks were intruded by a composite batholith of tonalite and granodiorite, and minor quartz monzonite and granite (tonalite suite). Since, the tonalite suite rocks contain a penetrative foliation associated with recumbent folding ( $D_1$ ), this suite is pre- to early syn-deformation. Both the volcanic section of the greenstone belt and the tonalite suite formed during active north-directed subduction prior to collision along the GLTZ.

Continental collision along the GLTZ resulted in progressive deformation of the volcanic-plutonic arc about 2700 Ma. Development of the magmatic arc ended with the onset of large-scale north-directed recumbent folding ( $D_1$ ) that was followed by upright folding ( $D_2$ ) and development of shear zones ( $D_3$ ). A trondhjemite to granite suite occurs as intrusive stocks and plugs both interior and exterior to the volcanic section. Intra-belt stocks and rhyolite dikes are aligned subparallel to axes of  $F_1$  and  $F_2$  folds but cut by shear zones. The trondhjemite to granite suite is syn- to late-upright folding. A hornblendite-diorite-syenite suite occurs as scattered weakly foliated pipe-like to stock-sized bodies. While relative age with respect to the trondhjemite to granite suite is not established in the field, we interpret this suite as coeval with large scale shear zones ( $D_3$ ) that define boundaries of lithostratigraphic blocks within the volcanic section. Both trondhjemite to granite and hornblendite-diorite-syenite suites were emplaced during collision along the GLTZ. A late granite suite is found throughout the area and consists of massive rocks cutting foliated rocks. These rocks are the youngest Archean granitoid rocks and are post-tectonic with respect to collision along the GLTZ.

In the Canadian portion of the southern Superior Province, Sutcliffe (1991) has identified a temporal progression of granitoid rocks. A foliated tonalite suite is related to arc construction during subduction. Syntectonic foliated tonalite was emplaced during collision. Granite to granodiorite, diorite to syenite and two-mica granite suites are late- to post-tectonic. Temporal progression of Archean granitoid rocks in the Ishpeming greenstone belt and vicinity is comparable to the southern Superior Province as a whole.

This research was partially funded by the Michigan Geological Survey, U.S. Geological Survey (COGEOMAP), and Western Mining Corporation (USA).

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## Gravity Model of the Wolf River Batholith

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Recently acquired gravity data has more extensively delineated the approximately -30 mGal Bouguer gravity anomaly associated with the Wolf River Batholith, which outcrops in northeast Wisconsin. This anomaly is superimposed on the Wisconsin Gravity Minimum, a -60 mGal Bouguer gravity anomaly over the Wisconsin Arch.

The gravity field was upward continued to eliminate short-wavelength, shallow anomalies that tend to mask the field associated with the batholith. A second filter was applied to minimize the affect of the Wisconsin Arch in the area associated with the Wolf River Batholith.

Modeling of the filtered gravity field indicates that the batholith has a variable thickness, averaging between 1.5 and 2 km thick. This model supports the conclusions of Anderson (1980), who proposed on the basis of geochemical data, that the batholith was emplaced at relatively shallow depths (less than 4 km), and that it is fairly thin (less than 5 km thick). The model also suggests that the batholith does not extend far past its western, eastern, and northern outcrops, but does extend a considerable distance in the subsurface beyond its southern boundary.

Although the Wisconsin Gravity Minimum reaches its most negative value over the batholith, the Wolf River Batholith is not fully coincident with nor the sole cause of the Wisconsin Minimum.

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Textural and Compositional Study of a Manganiferous Iron-Formation, Emily District, Cuyuna Range, with Implications for Original Deposition and In Situ Leaching of Manganese

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U.S. Bureau of Mines

The U.S. Bureau of Mines is conducting geologic and geochemical characterization studies on drill core from the manganiferous iron-formation of the Emily District, Cuyuna Iron Range, Minnesota to determine whether in situ leach mining techniques can be utilized to recover high-grade manganese solutions from low-grade manganese ore.

In this study, three lithologic units of the manganese-oxide-bearing iron-formation were identified and consist of a thinly bedded, chert-hematite iron-formation; a well laminated, fine-grained to thickly bedded, granular, variably sandy, manganese-oxide-hematite-goethite iron-formation that contains interbeds of chert; and a basal unit of manganese-oxide-bearing oolitic to sandy chert. The presence of well-rounded, terrigenous quartz-sand-grains; hematitic and manganese-oxide granules; and a variety of oolite-types containing combinations of quartz, hematite, and manganese-oxide suggest a near shore depositional environment for the granular subunits of the iron-formation. The average assay grade of the three units is <0.1 % Mn, 11.4 % Mn, and 10.1 % Mn, respectively. The manganese minerals identified in the Emily district are manganite, cryptomelane, hollandite, braunite, and lithiophorite.

Microscopic textural relationships and microanalysis of the composition of ore and gangue mineralogy are important to the success of in situ leach mining. The leach fluid must be able to access, selectively solubilize manganese, and then transport it utilizing the natural permeability of the rock. Manganese mineralization is strongest in the granular facies of the iron-formation, likely because of higher intergranular porosity and higher permeability than in the finely bedded to laminated nongranular strata. Manganese-oxides commonly have replaced original chert matrix of the granular facies. Preliminary experimental data on similar manganiferous rocks to date have shown that aqueous  $\text{SO}_2$ -solutions selectively dissolve Mn from rocks in which fine-grained manganese-oxides and iron-oxides are intimately mixed, as in the Emily rocks. Porosity/permeability data on core samples from the Emily suggest that leach solutions should more favorably access manganese-oxides from the more granular strata of the iron-formation than from strata of well-laminated, very fine-grained iron-formation or chert.

# The Petrology and Geochemistry of the Spirit Volcanogenic Massive Sulfide Prospect, North-Central Wisconsin.

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University of Minnesota

The Spirit zinc-lead-copper volcanogenic massive sulfide prospect is located within the Somo massive sulfide district of an Early Proterozoic Penokean volcanic-magmatic terrane in north-central Wisconsin. A petrographic and geochemical study of the lithologic package that hosts the sulfide was made. Four major interbedded rock units were identified and include tholeiitic mafic and calc-alkaline felsic volcaniclastic pyroturbidites, felsic fragment-rich debris flows, and minor meta-carbonate. According to data from trace element discrimination diagrams and the finely bedded nature of the rocks, the bimodal submarine volcanics were erupted in an island-arc tectonic setting and were deposited subaqueously, distally from the eruptive center, perhaps in a back-arc basin.

Regional dynamothermal metamorphism produced isoclinally folded rocks in which the rock fabric is well foliated ( $63^\circ$ ) and lineated. Prograde metamorphic mineral assemblages reached the staurolite-quartz subfacies of the almandine-amphibolite facies of metamorphism. Garnet-biotite geothermometry yields a maximum temperature between  $410^\circ$  and  $500^\circ$  C and sphalerite-pyrrhotite-pyrite geobarometry indicates a metamorphic pressure of 5 kb.

The main sulfide-bearing mineralized horizon is characterized by enrichment of Fe, Cu, Pb, Z, Mg, Mn, Ti, Ga, and Sc and depletion in Si, Na, K, Rb, Sr, and Ba. The stratiform, stratabound sulfide lens (up to 9.3 m thick) is developed in a muscovite-quartz schist which occurs below a chloritized mafic schist. The felsite occurring above the chloritized mafic schist contains quartz-pyrite laminae (0.5 cm thick) with low base metal content. These laminae are interpreted as being a hydrothermal exhalite. Based solely on the rare earth element pattern of 3 felsic samples and the model proposed by Campbell et al. (1984), the felsic unit with the quartz-pyrite laminae may be genetically capable of hosting an economically significant massive sulfide deposit.

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## PROCESS RATES DURING MIDCONTINENT RIFTING: CLUES TO THE ORIGIN OF THE MIDCONTINENT RIFT SYSTEM

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Two developments in recent years, the acquisition of deep seismic reflection profiles (Cannon and others, 1990) and the determination of a precise geochronologic framework (Davis and Sutcliffe, 1985; Palmer and Davis, 1987; Davis and Paces, 1990), make it possible to study quantitatively processes related to the Midcontinent rift system (MRS). One step in these studies is to estimate rates of processes. This paper presents the results of some simple calculations which place considerable constraint on process models and, by comparison to rates of younger and modern processes, helps clarify the nature and cause of rifting.

Subsidence rate: Because numerous stratigraphic horizons that can be traced on seismic sections are precisely dated, subsidence curves can be drawn. Figure 1 shows a curve determined for the western Lake Superior region near the rift axis. Subsidence accelerated for the 15 m.y. during which the voluminous basalts were erupted but then abruptly slowed near the end of volcanism and continued at a slower rate for at least several tens of million years during postrift sedimentation. The average subsidence rate during volcanism was about 1.3 mm/yr but may have exceeded 5 mm/yr during the most rapid subsidence toward the close of volcanism. During sedimentation, subsidence averaged only a few tenths of a millimeter per year at most.

Magma generation rate: For the entire rift I estimate that roughly  $2 \times 10^6 \text{ km}^3$  of volcanic rocks were erupted. A comparable amount of intrusive rock was probably emplaced within and at the base of the crust, so about  $4 \times 10^6 \text{ km}^3$  of basaltic magma was generated in about 15 m.y. The magma generation rate is thus about 0.25 km<sup>3</sup>/yr.

Eruption rate: Average eruption rate was about 0.13 km<sup>3</sup>/yr. The eruption rate may have changed significantly with time, but that is difficult to quantify because of incomplete preservation of the older flow sequences which originally extended well beyond their present outcrop belts. The Portage Lake Volcanics, which probably erupted from a single center near the end of volcanism, had an eruption rate as high as 0.2 km<sup>3</sup>/yr.

Extension rate: A common estimate of the present extension across the rift in the Lake Superior region is about 50 km. The rift probably closed about 30 km during later compression, so original extension was probably about 80 km. Assuming that extension and volcanism were coeval, I calculated the extension rate averaged 5 mm/yr.

Comparison to younger processes: One of the most striking features of the rift is the great volume of basalt produced in a relatively short time. The average eruption rate of 0.13 km<sup>3</sup>/yr is about half of the peak production rate for Columbia River basalts, which maintained that rate for only about 0.5 m.y., and about one-fourth the average eruption rate of the Deccan basalts, probably the most rapidly erupted basalts of the Phanerozoic (Baksi, 1988). However, the eruption rate for the Portage Lake Volcanics matched that of the Columbia River basalts and was half that of the Deccan. Because basalts were probably being erupted from other centers synchronously with the Portage Lake,

the MRS, toward the end of its volcanic phase, may have matched or exceeded the eruption rate of the Deccan. The eruption rate for the Portage Lake Volcanics was about twice the modern rate of the Hawaiian hotspot (Swanson 1972), the most vigorously erupting volcanic center of the modern earth.

There are clearly no modern analogs for the volcanism of the MRS, and only rarely in earth history have continental flood basalts been erupted at rates comparable to the MRS. On the modern earth, the only tectonic setting in which basaltic magma is generated at rates comparable to the MRS is midocean ridges. A ridge 2,000 km long (about the length of the MRS) spreading at a rate of 5 cm/yr produces about  $0.7 \text{ km}^3/\text{yr}$  of basaltic magma, or about 3 times the production rate of the MRS. However, the extension rate for the MRS is an order of magnitude less than such a ridge. The MRS, therefore, was 3 to 4 times more productive of magma per unit of extension than are modern midocean ridges.

These relationships require that the mantle beneath the MRS was much hotter than mantle beneath modern midocean ridges in order for great volumes of magma to have been generated during extension. They are consistent with origin of the MRS magmatism in response to the arrival of the head of a new mantle plume beneath the region at about 1.1 Ga. The great burst of basaltic volcanism, but the limited time span for it and related extension, represents the time required to dissipate the anomalous amount of thermal energy in the plume head.

Postvolcanic sedimentation: Figure 1 illustrates the marked difference in subsidence rate during volcanism from that during later sedimentation and implies that the sedimentary rocks of the Oronto Group and younger sequences were not deposited in an active rift. The rate of development of the sedimentary basin is consistent with the rate of subsidence caused by decay of the rift-generated thermal anomaly in the mantle, augmented by isostatic compensation of loading by the sedimentary fill, and does not require postvolcanic extension. Although thick accumulations of coarse, nearly massive conglomerate, such as the Copper Harbor Conglomerate, are generally assumed to be evidence for extensional uplift of adjacent highlands, the sedimentation rate is not extreme and may not require active tectonism. As indicated by ages of underlying Portage Lake Volcanics and interlayered flows (Davis and Paces, 1990), the accumulation rate of even the coarsest conglomerates was about 1 m per 5,000 yr. The continued supply of coarse alluvium during more than a kilometer of sedimentation likewise does not require extension, and could have been accomplished by isostatic renewal of original rift-flank uplifts during their erosional destruction.

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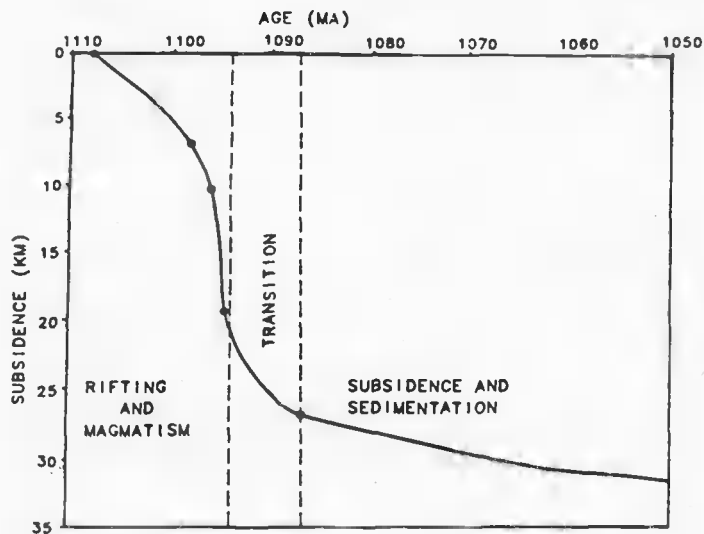


Figure 1. Subsidence curve for the axial region of the Midcontinent rift beneath Lake Superior. Solid circles identify stratigraphic horizons for which precise U-Pb radiometric ages are known (Cannon, in press).

# ISOTOPE AND PALEOMAGNETIC DATING OF WEATHERED GRANITE BELOW THE PRECAMBRIAN-CAMBRIAN CONTACT IN NEILLSVILLE, WISCONSIN

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The Precambrian-Cambrian (PC-C) contact in central Wisconsin is represented by a nonconformity between the Upper Cambrian Mount Simon Sandstone and the late Proterozoic crystalline rocks. In Neillsville, the section below the contact is a 3 m thick zone of weathered granites. Petrographic studies of the weathered granite show that the pre-Mt. Simon paleosol is overprinted by diagenetic reactions with pore fluids from the Mt. Simon Sandstone [Hay and Liu, 1991]. The abundance in authigenic K-feldspar in the paleosol is attributable to widespread hydrological events that occurred in the Upper Mississippi Valley during the mid- and late Paleozoic. Potassium-argon dating of an illitic clay and authigenic K-feldspar in the altered granite within 2 meters of the PC-C in Neillsville yielded, respectively,  $385 \pm 9$  Ma and  $411 \pm 10$  Ma ages. These ages are compatible with previously reported ages of potassic diagenesis in the Upper Mississippi Valley [Hay et al., 1988; Lee and Aronson, 1991]. Measured  $\delta^{18}\text{O}$  values of the illitic clay and K-feldspar are not in equilibrium, suggesting a probable higher diagenetic temperature of the K-feldspar than of the illitization.

We have conducted a paleomagnetic study to determine if the weathered granite was remagnetized during the diagenesis. Eighteen oriented block samples were collected from three quarries in Neillsville. At least four 1" diameter x 7/8" length specimens were prepared from each sample. NRM intensity measurements, thermal demagnetization, and alternating field demagnetization were conducted at the Institute of Geomagnetism and Rock Magnetism at the University of Minnesota. (Help from the UM Magnetism Group is gratefully acknowledged.) The samples were progressively demagnetized at temperatures up to 650°C at 10°C increments and in alternating fields up to 80 milliteslas and 10 mT increments. Principal component analysis was conducted to delineate linear segments from the measurement results. For samples that do not yield linear segments, the magnetization step before a substantial drop in NRM intensity is used as the representative direction. Orthogonal vector projections are used to help the component analysis. The acceptability of the results from individual blocks is based on the following criteria:

- (1) stability of the magnetic component upon demagnetization,
- (2) efficiency of the demagnetization method as indicated by the reduction of NRM intensity during the demagnetization, and
- (3) consistency of magnetic components in specimens prepared from the same sample.

Thermoremanent curves obtained from thermal demagnetization of the samples reveal dominant blocking temperatures at about 300-350°C, indicating ilmenite or/and a titanomaghemite as the principal magnetic carriers. About 20% of the specimens do not yield stable NRM components and specimens from three blocks do not show consistent directions. The large number of unstable samples reveals substantial weathering effects. The magnetic components obtained from the stable samples are not randomly distributed, but do not cluster about the present field. No tilt correction has been applied to the specimens; the attitude of the PC-C contact surface suggests no major post-

Proterozoic tectonic rotation of the sites. The representative directions from the acceptable samples appear to form two general clusters, one with a southwesterly to westerly declination and a second one with a southeasterly declination. The first cluster yields a mean direction at  $D=263^\circ$ ,  $I=50^\circ$ , and a virtual geomagnetic pole at  $146^\circ\text{W}$ ,  $23^\circ$ ; the second cluster yields a mean direction of  $D=140^\circ$ ,  $I=45^\circ$ , and a pole at  $125^\circ\text{E}$ ,  $9^\circ$ . The two poles are compared to the paleomagnetic poles of stable North America compiled by Irving [1977]. The first component can be interpreted as a late Proterozoic overprint, as indicated by the similarity in paleopole coordinates. A similar magnetic component is present in the 1.52 Ga-old syenite in Wausau, eastern Wisconsin, [Zich et al., 1986] and in Keweenaw-age mafic dikes in central Wisconsin [Chan, 1991]. The presence of similar magnetic components in these rocks plausibly implies a widespread remagnetization event during the late Proterozoic. The second magnetic component in the Neillville granite appears to be a Cambrian-age overprint, and can be interpreted as a chemical remanent magnetism acquired during the weathering and formation of the paleosol. None of the components observed appears to be late-Paleozoic age. Unfortunately, the poorly constrained Silurian-Devonian segment of the apparent polar wander path of stable North America renders a conclusive comparison impossible. Most Silurian-Devonian paleomagnetic results, however, show paleopoles at high latitudes of about  $40^\circ$ . The low latitude of the paleopole obtained from Neillville, therefore, argues against a Devonian remagnetization.

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## Implications of Strain and Magnetic Anisotropy Studies for the Penokean Orogeny, Upper Michigan

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This study applies geometric strain analysis and magnetic anisotropy techniques to the Michigamme Slate to constrain the kinematics of the Penokean Orogeny. The Michigamme Slate (Baraga Group, Marquette Supergroup) of Upper Michigan is present in the allochthon and parautochthon of the 1.88 Ga Penokean Orogeny. Our data was collected within the allochthon on a 15 mile traverse from Covington, MI to the south along highway M-95.

Early sedimentary rocks of the Marquette Supergroup were deposited on a passive continental margin. Post passive-margin rifting was followed by rapid subsidence and the deposition of turbidites from two source areas: a volcanic arc to the south, and a continental source to the north (Barovich, 1989). These turbidites are contained in the Michigamme Slate of Michigan and the correlative Thomson Formation of Minnesota. The allochthon is characterized by tight upright to overturned folds with steep axial-plane cleavage dipping  $54^{\circ}$  to  $S6^{\circ}W$ . Iron-carbonate concretions are pancake-shaped, and flattened in the plane of cleavage. The parautochthon exhibits significantly less intense folding, and mineral grains form vertically extended ellipsoids on the cleavage plane. The Michigamme Slate exhibits a mean shortening of 53%, compared to a (maximum) value of 64% for the Thomson Formation (Holst, 1985). Strain data measurements from the Michigamme Slate overlap those for the Thomson Formation for comparable locales in the orogen (Figure 1). Our strain data shows the pancake shape of the concretions, which we interpret as the result of an homogeneous pure flattening strain ( $x : y : z = 1.0 : 1.0 : 0.2$ ). In the northern area of the Thomson Formation, Holst (1985) finds  $x : y : z = 1.5 : 1.0 : 0.2$ . The Thomson Formation's strain ellipsoid has strong vertical extension accompanied by flattening.

Preliminary magnetic anisotropy (ams) axial orientation values indicate maximum at  $N20^{\circ}W @ 55^{\circ}$ . This is nearly perpendicular to the cleavage plane, and hence the maximum extension found through our strain analysis. The intermediate and minimum ams directions fall very close to the cleavage plane. The ams strain intensity values were found to be very minor when compared to the data from the concretions. As indicated in Figures 1 and 2, the ams data is a major underestimation of the strain amount found within the Michigamme Slate. The ams data, shown more clearly in Figure 2, can be seen to exhibit little indication of strain: magnetic anisotropy does not appear to correlate with conventional strain anisotropy in either the Thomson or Michigamme Formations. We found good correlation with Davidson's ams values for the Thomson Formation, but neither ams study exhibits correlation with the strain observed through conventional strain analysis.

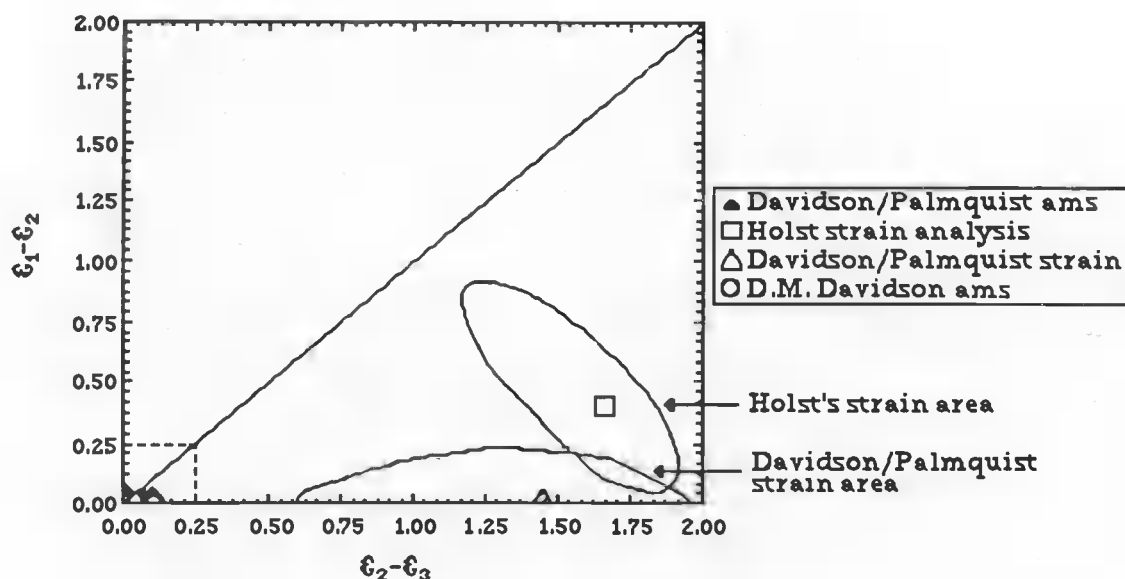


Figure 1: Logarithmic deformation plot.

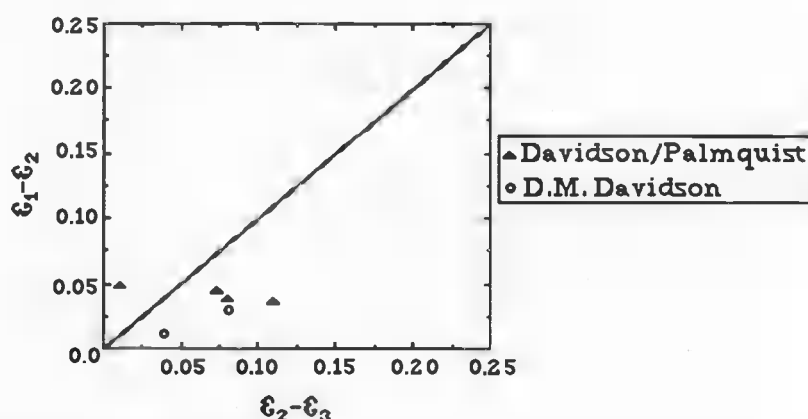


Figure 2: Logarithmic deformation plot showing the ams data points.

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# MAGINO, THE MAKING OF A MINE

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## ABSTRACT

The Magino Gold Mine is located 38 miles NE of Wawa, Ontario. There was limited gold production in the late thirties. The present operation was officially opened in October 1988. It is a 700 ton per day decline accessed mine with ore coming from several small blast-hole and shrinkage stopes.

The host for the gold is the Webb Lake Granodiorite Stock which was intruded into the Goudreau Deformation Zone. The ENE striking deformation zone overprints the generally EW striking isoclinally folded volcanic and sedimentary rocks which make up the east-end of the Michipicoten Greenstone Belt. The ore-shoots are controlled by dextral dilatancy associated with the Goudreau Deformation Zone. Shearing, bleaching and silicification occurred with the gold emplacement.

The history of exploration and present operation are discussed.

**PRELIMINARY REPORT, GEOLOGY AND GEOPHYSICS OF THE TERRA/PATRICK #7-22 WILDCAT HYDROCARBON TEST, MIDCONTINENT RIFT, KEYSTONE TOWNSHIP, BAYFIELD COUNTY, WISCONSIN**

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The Terra/Patrick #7-22 borehole, located in the southwest quarter, northeast quarter, Section 22, Township 47 north, Range 6 west, is being drilled as a joint venture between Terra Energy, Inc. of Traverse City, Michigan and Patrick Petroleum Company of Jackson, Michigan, operating under a farmout arrangement from Amoco Production Company (USA). This well-site is situated approximately 5 miles northeast of the Hazel Hills site announced by Amoco in the Spring of 1985. This latter borehole was never drilled because of a lack of existing exploration drilling legislation and the mid-1980's decline in crude oil value.

The Terra/Patrick borehole was spudded shortly after midnight, March 9, 1992. The state-issued permit allows drilling to 6000 feet, with restrictions concerning control of mud chemistry additives, casing standards, and analyses of cuttings. Extensive and involved public hearings were conducted in Bayfield County prior to the issuance of the drilling permit.

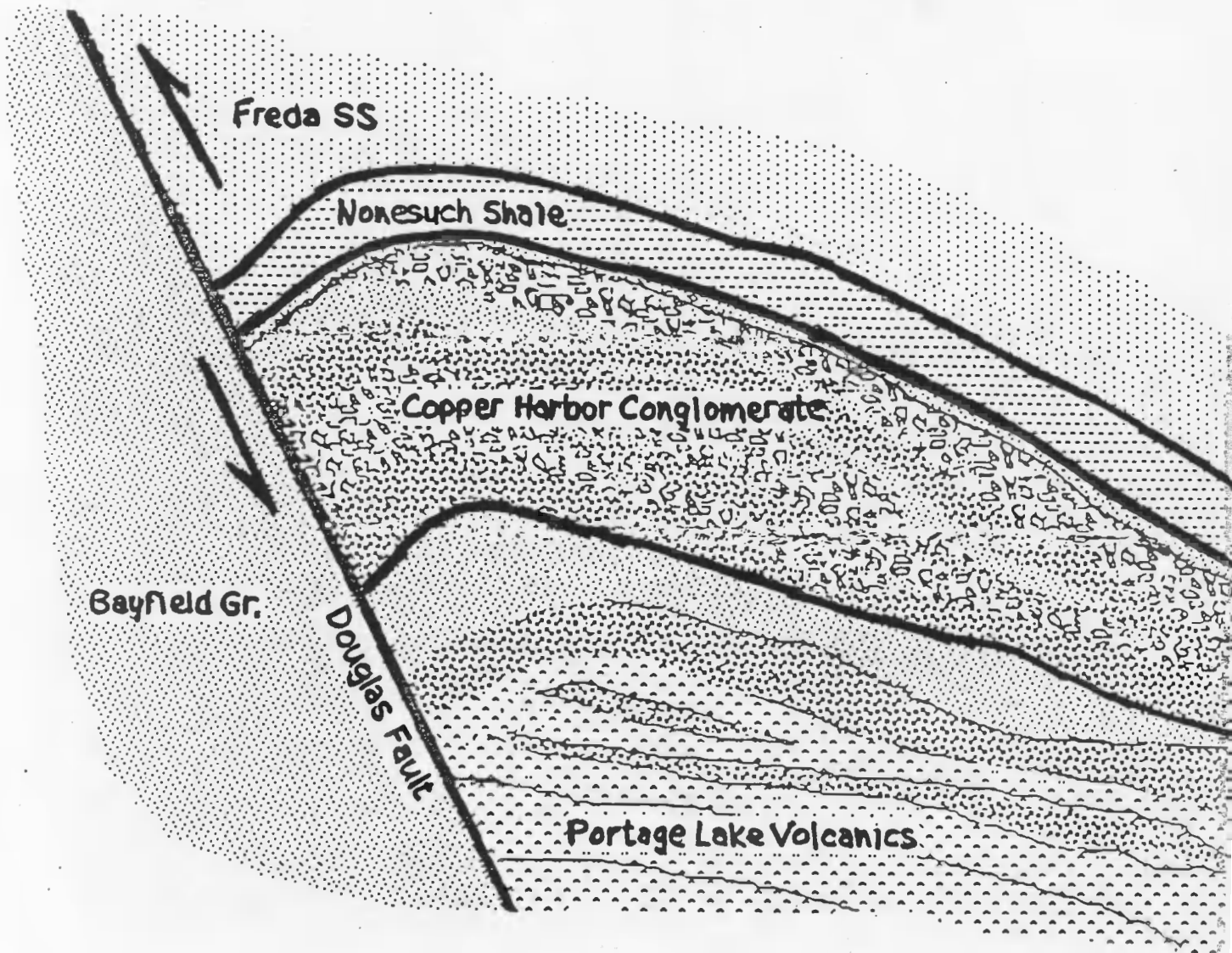
This borehole, a central rift horst test, will be the fourth conducted along the Midcontinent Rift System since 1984. The first (Kansas, 1984) drilled a reversed rift sequence caused by faulting. The second (Iowa, 1987) tested the western, half-graben flank of the rift. The third, also a flank test, was initiated in the Upper Peninsula of Michigan in 1987. All have failed to find hydrocarbon reserves.

The Bayfield County (Chequamegon) prospect is seismically identified as a large four-way anticlinal structure caused by drag folding along the hanging wall of the Douglas fault (Fig. 1). The anticline, with an axis that parallels the strike of the Douglas fault, extends over a surface area of approximately 37,000 acres (60 square miles) and has several thousand feet of structural closure. Reservoir quality strata are being sought in all three units which comprise the Oronto Group of volcanoclastic rocks--oldest to youngest, the Copper Harbor, Nonesuch, and Freda formations.

Depending upon the final drilling outcome (see note below), additional information will be available at the time of presentation of this report.

At the time this abstract was prepared (March 24, 1992), the subject borehole was drilling in excess of 3500 feet. Simultaneously an injunction action, filed on behalf of the Lac Courte Oreilles band of Chippewa Indians, was in its third day of testimony in Dane County (Wisconsin) Circuit Court.

FIGURE 1.  
CHEQUAMEGON PLAY SCHEMATIC



RESERVOIR - Basal Nonesuch Sand and Copper Harbor Fm.

SOURCE - Nonesuch Shale

SEAL - Nonesuch Shale

## PRECAMBRIAN HYDROCARBON POTENTIAL OF THE WESTERN GREAT LAKES

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Hydrocarbon shows have been reported in the western Great Lakes since 1852. Occurrences include stained core, surface exposures, and indigenous shows in mine roof strata. All emanate from a single source, the Nonesuch Formation (maximum age of 1.074 Ga) of the Oronto Group, Keweenawan Supergroup, a (Midcontinent) rift derived, middle Proterozoic volcanoclastic sequence. Indirect age-dating (Rb-Sr) indicates live oil hosted by the Nonesuch Formation has a minimum age of 1.047 Ga.

Nonesuch Formation distribution along strike is mapped for 300 km, from the Upper Peninsula of Michigan to within 30 km of the WI/Mn border. Borehole stratigraphic studies suggest lateral deposition into rift flank basins. Reflection correlations indicate source rock thickness, measured in outcrop as maximum 215 meters, to be tectonically controlled. Anticlinal, drag folding, unconformity, and fault trap structural geometries are seismically identified. Stratigraphic trapping may be associated with varying depositional environments. Intergranular porosity exceeds 13 percent, with fracture porosities common.

Recognized anticlinal closure is of a scale defined by seismic profile spacing approximating 8 to 10 km, extending to two-way-travel depth of 3 to 4 seconds. Field studies suggest primary reservoirs would be spatially/time associated with crustal-extension, thermal events. Secondary hydrocarbon charges into axial and flank domains may have been controlled by substitution of compression for extension tectonics, causing stabilization of oil and gas accumulations prior to initiation of Phanerozoic time. Maturation analyses favor gaseous over liquid reservoirs.



Location of hydrocarbon test boreholes drilled in Wisconsin through 1992.

Evaluation criteria pertaining to the hydrocarbon (HC) potential of the Lake Superior basin segment of the Midcontinent Rift System. →

### Evaluation Criteria

#### Source

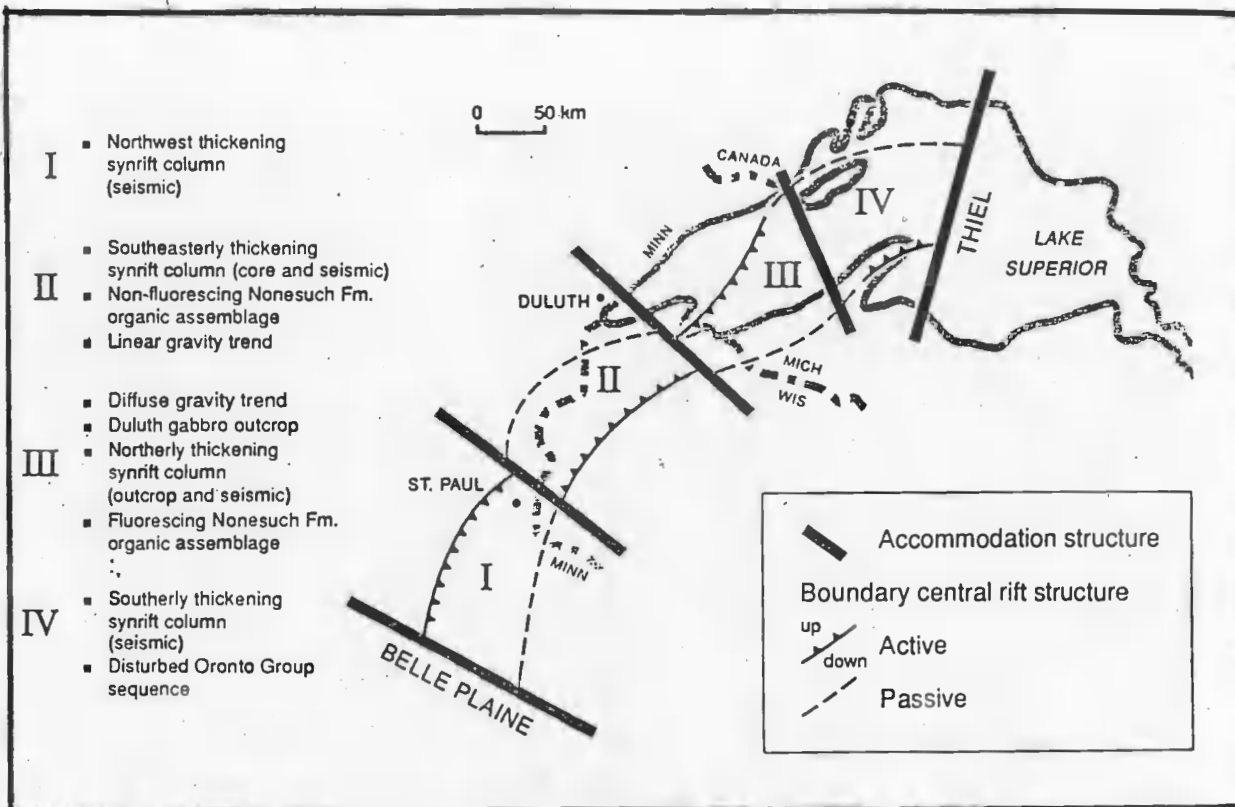
- Nonesuch Formation: ~1.074 Ga in age
- TOC averages 1.5%, White Pine Mine, Michigan

#### Maturation

- Geothermal gradient within normal to high range
- Oil seeps paraffinic, low in sulfur, and 32° API

#### Migration

- Principal Proterozoic structure in place at time of primary migration
- Early extension-phase migration followed by later compression-phase migration
- Crude found intergranular and along fractures



Differentiation of Midcontinent rift in Lake Superior basin. Each rift unit must be individually evaluated for HC potential.

### Reservoir

- Reservoir-quality strata within Copper Harbor Conglomerate, Nonesuch and Freda Formations
- Oronto Group intergranular porosity ranges from 7-15%

### Structure

- Two stage tectonic history created multiple structure combinations
- Structures include fold, fault, and stratigraphic traps

### Seal

- Lake Superior region rift clastic infill is 60/40 shale/sandstone ratio
- Mineralization seals formed by calcite crystallization

1991 COGEOMAP Gravity Mapping Program in West-Central Wisconsin:  
The Driftless Area

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During the summer of 1991, nominal one-mile grid gravity coverage was extended to an area bounded by 44 & 45 degrees latitude and by 90 and 90.5 degrees longitude. Stations are located at surveyed spot elevations posted on USGS 1:24000 topographic sheets. Northern Illinois University's LaCoste-Romberg gravity meter G409 was used. Data are tied to the State of Wisconsin Primary Gravity Base Station Network (Ervin, 1983), which is in turn tied to the International Gravity Standardization Network-1971 (DMAAC, 1974). Older data have been merged with these data to yield a much more detailed representation of the Bouguer gravity anomaly field than was previously available.

The northeast half of the area is underlain by glacial deposits that are in turn underlain by Cambrian sedimentary rock, primarily sandstone, except in the northeastern corner, where lower Proterozoic intrusive rock, primarily granite, underlies the till. The southwestern half of the survey area extends into the driftless area and is dominated by the Cambrian sandstone that is covered by the glacial deposits in the northeast, although lLower Proterozoic and uUpper Archean rock crop out along several of the river systems. The extreme southwest corner of the area also contains a few remnants of the Ordovician Prairie du Chien dolomites.

Much of the area is covered by marsh and swamp, and the surface becomes more dissected as the Mississippi River is approached to the west. In this type of terrain, the road system tends to follow the topography rather than the section lines, so the station distribution deviates significantly from a one-mile grid over much of the area. Access problems were further compounded by the high rainfall during the field season that flooded many roads. We anticipate obtaining supplementary data in these areas in 1992.

Due to the dissected topography in the southwest, terrain corrections were applied to the data. The Bouguer gravity anomaly field is dominated by broad minima, but ascends in the southwest to values above -15 mgals and in the northwest to over -20 mgals. The field descends below -80 mgals in an east-west trending minima located in the southwestern corner of Marathon County and west of Marshfield. This minima is flanked on the

north by a fault that separates it from a relatively positive anomaly apparently associated with metamorphosed early Proterozoic mafic to ultramafic intrusive rock (Mudrey and others, 1982). A second relatively positive anomaly lies south of the minima in Wood County. The source of this anomaly is not known.

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THE PALISADE RHYOLITE, LAKE COUNTY, MINNESOTA:  
A CRYPTIC RHEOIGNIMBRITE IN THE NORTH SHORE VOLCANICS

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The Palisade rhyolite, >90 m thick, is one of the most easily accessible of the several large rhyolite flows in the NSVG. Although it has been broken up somewhat by faulting, it can be traced with certainty for 18 km and possibly for 29 km northeast from Beaver Bay. In most outcrops it is massive and porphyritic, with a few percent of  $\beta$  quartz, alkali feldspar, and oxidized ferromagnesian silicate phenocrysts. Its groundmass is made of fine-grained alkali feldspar and flow-aligned tabular quartz paramorphs after primary tridymite. With a flow breccia near the top at Illgen City and folded flow-banding near the top and bottom, it looks like an unusually large and widespread lava flow, perhaps like other highly mobile, high-T silicic lava flows recently described from various Tertiary and Mesozoic provinces.

Close petrographic examination of the base and top, however, indicates that the Palisade rhyolite was emplaced as a hot pyroclastic flow that completely welded to the base, and flowed after welding - a rheoignimbrite. Both in the laminated top breccia zone and in the basal meter only, thin sections reveal a groundmass of welded glass shards. Over a narrow transition zone of one or two meters above the base these shards are completely deformed until only a fine, planar flow lamination is present. This transition zone contains strong lineations that show the direction of flow after welding, and flow-folds, some isoclinal, are developed in the overlying zone. This passes upward into the massive interior that makes up the great bulk of the flow.

The Palisade rhyolite illustrates the necessity of careful petrographic as well as field examination of the tops and bases of felsic flows in order to interpret their origin correctly.

**Petrology and Provenance of a Conglomerate Facies of the  
Jacobsville Sandstone: Ironwood to Bergland, Michigan**

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West of Lake Gogebic, from Ironwood to Bergland, Mich., the Late Proterozoic (Keweenawan) Jacobsville Sandstone is dominated by conglomerates and coarse lithic arenite in contrast to areas farther east where it is a finer grained, submature to mature, quartzose, feldspathic and lithic arenite with minor shale, siltstone, and conglomerate (Kalliokoski, 1982). This paper presents data indicating a southern source for these western conglomerates and coarse sandstones, which is consistent with a current theory of active thrust faulting south of the Jacobsville along the Pelton Creek fault (Cannon and others, 1990; Sims, 1990).

The conglomerate is clast-supported and poorly sorted with a coarse sandy matrix. Clay fills most interstices and coats all grains. The clasts are subrounded to well rounded and range in size from 3-15 cm. Clast lithologies are predominantly iron-formation and quartzite from Early Proterozoic units and vein quartz from Archean units. Only minor amounts of volcanic clasts (probably from Keweenawan units) are present.

Medium to very coarse sandstone from the TT1 and TT6 drill cores, located approximately 16 km east of Wakefield, were studied. Two general trends can be seen: 1) a decrease upsection in mafic and silicic volcanic clasts believed to be derived from Keweenawan units and 2) an increase upsection in granitic clasts believed to be derived from Archean units. Iron-formation clasts are rarely seen in the sand-size fraction making it difficult to distinguish sediment contributed by Early Proterozoic units. These trends indicate initial erosion through a cover of Keweenawan rocks and presumably through Early Proterozoic rocks into the Archean basement.

Dips within the western portion of the Jacobsville Sandstone range from 34° N in the lower part of the section to 9° N in the upper part, excluding areas where the Jacobsville has been dragged up on the Keweenaw fault. In contrast, most of the Jacobsville east of Lake Gogebic is relatively flat lying. The fanning nature of the dips west of Lake Gogebic is consistent with sedimentation on a fault block that is rotating to the north.

This fault block rotation was caused by thrust faulting along the Keweenaw fault to the north and the Pelton Creek fault to the south. Uplift and erosion of Keweenawan, Early Proterozoic and Archean units along the southern end of this fault block is the source of the conglomerates and coarse sandstone in the Jacobsville Sandstone west of Lake Gogebic.

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PETROLOGY AND STRUCTURE OF A RAPAKIVI BODY FROM EAST-CENTRAL MINNESOTA.

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A 10 m. wide granitic dike located in the Meridian Aggregate quarry in Waite Park, MN, has an east-west strike and dips to the south at a steep angle. This tabular body is bounded on the north and south sides by nearly continuous parallel basaltic dikes, and is crosscut by a small basaltic dike with a N60E strike. Variable sized basaltic xenoliths are found within the dike, one of which is 1 m. by 10 m. in dimension. The north contact of the dike appears to be structural, with calcite-filled slickensided surfaces within the basalts near the contact and mineralized shears containing epidote within the dike. The south contact is undulatory with a wave length of 5 to 10 m.

The rapakivi body displays a porphyroblastic texture composed of potassium feldspar and quartz accompanied by minor amounts of biotite and saussuritized plagioclase. Texturally the potassium feldspar grains at the margin are small (.1-.5 cm), do not display obvious concentric laminations, and are anhedral. As the center of the body is approached, the potassium feldspar grains increase in size (.3-2.1 cm), become subhedral to euhedral and display obvious concentric laminations. Often times small anhedral cores are visible.

An aphanitic matrix comprises 45-55 percent of the Rapakivi body. The matrix consists of vermicular quartz either rimming large potassium feldspar or quartz grains or is completely networked with smaller potassium feldspar grains forming a granophyric texture. The remainder of the matrix is composed of small (less than .2 mm) strained quartz grains, altered feldspar and biotite. Also present are accessory minerals such as allanite, zircon, epidote, chlorite and calcite. The latter three are confined to regions of fracture or shear.

Shearing is extremely common at all scales and appears to have played a dominant role in the development of this body. Metasomatic activity during the shearing process may have lead to the development of both the observed mineral assemblage and the Rapakivi texture displayed in this rock body.

## Provenance of the Animikie Group, NE Minnesota, based on Nd and Pb isotopes

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Nd and Pb isotope data (Fig. 1, Fig. 2) on samples from the Animikie Group in the Mesabi Range reflect the progression of the northern margin of the Animikie basin from an early near-shoreline facies with northern sources, to a later relatively deep-water facies with sediments derived from rising mountain ranges to the south associated with the Penokean orogen. Based on facies analyses, the northern shoreline of the Animikie basin is interpreted to have been near the present northern margin of the basin during deposition of the Pokegama Quartzite and Biwabik Iron-formation [1,2]. The overlying Virginia Formation is dominated by argillite with some thin, very fine graywacke intervals [3]. Throughout the interval are infrequent, thin, olive green tuff horizons. Lucente and Morey [3] interpret the deposition of the Virginia Formation to have been dominantly from pelagic processes in a relatively deep-water environment.

The petrogenesis of early Proterozoic mafic rocks in central Minnesota was studied by Horan et al. [4], who concluded that these rocks are arc-related. The Pb and Nd isotopic compositions of these mafic rocks are the same as the geographically associated granitic plutonic rocks [5]. The  $\epsilon_{\text{Nd}}$  at 1850 Ma for these rocks is dominantly 0 to -3, with depleted mantle model ages of 2.1 to 2.4 Ga [4,5]. Therefore the sources for these rocks have evidence of a LREE enriched history or were contaminated by an old, LREE enriched component [4,5]. The initial Pb isotope composition of the K-feldspars from the granitic rocks precludes the Superior Province as the contaminating component [5]. Spencer [5] suggested that these are mantle characteristics or that there is a contribution from the early Archean rocks of the Minnesota River Valley terrane. The Nd isotopic compositions are included in the field of central Minnesota magmatic rocks in Fig. 1 and the Pb isotopic compositions are included in the general field of Penokean magmatic rocks in Fig. 2. Van Schmus and Bickford [6] and Greenberg and Brown [7] suggested that the early Proterozoic igneous rocks of the Wisconsin magmatic terrane are also arc-related. The Pb isotopic composition of early Proterozoic rocks from Wisconsin [8] are included in the general field of Penokean magmatic rocks in Fig. 2, and the field Nd isotopic compositions at 1850 Ma [9] are shown in Fig. 1.

A silty unit of lower Pokegama Quartzite from Midway, Minnesota has  $\epsilon_{\text{Nd}} = -10.5$  at 1850 Ma (Fig. 1) and 2 whole rock samples lie along a 2.6 Ga slope in  $^{207}\text{Pb}/^{204}\text{Pb}$  vs  $^{206}\text{Pb}/^{204}\text{Pb}$  space, consistent with the interpretations of a Superior Province source based on petrology [1] and Pb isotopes from quartz and whole rock samples [10]. Both Nd (Fig. 1) and Pb (Fig. 2) isotopes from the Biwabik Iron-formation appear to record a mixture of early Proterozoic and Archean sources. This is consistent with the Nd isotope data of Gerlach et al. [11]. Two core samples from the upper slatey member (location 2 of the Mesabi Deep Drilling Project) from the Biwabik Iron-Formation have  $\epsilon_{\text{Nd}}$  of -6 at 1850 Ma (Fig. 1). The intermediate slate from the MINTAC mine, which Morey [1] interpreted as a tuff, has  $\epsilon_{\text{Nd}}$  at 1850 Ma of -3, in the range of the early Proterozoic igneous rocks from central Minnesota. Ten sedimentary samples from the Virginia Formation from location 2 of the Mesabi Deep Drilling Project have  $\epsilon_{\text{Nd}}$  at 1850 Ma of -0.9 to +0.3, and two tuffs have  $\epsilon_{\text{Nd}}$  at 1850 Ma of 2.8 and 3.2 (Fig. 1). All Virginia samples lie close to a 1.8 Ga slope in  $^{207}\text{Pb}/^{204}\text{Pb}$  vs  $^{206}\text{Pb}/^{204}\text{Pb}$  space (Fig. 2). The data preclude the Superior Province as a substantial contributor to the Virginia Formation. The early Proterozoic source indicated by the data, which is suggested to be the Penokean magmatic terrane to the south of the Animikie basin, is consistent with the evolution of the Animikie basin as a foredeep resulting from Penokean orogenesis [12].

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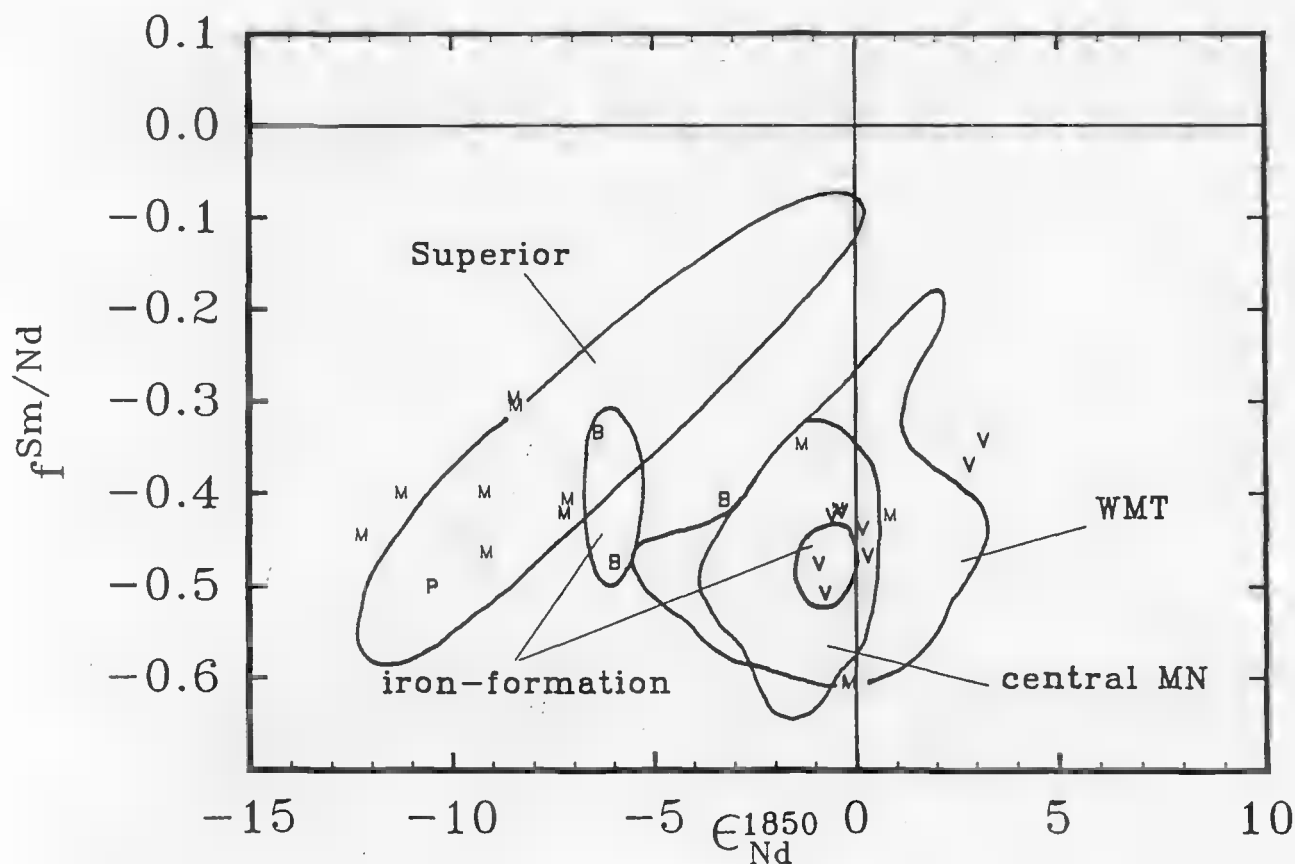


Fig. 1 Plot of  $f_{\text{Sm/Nd}}$  vs.  $\epsilon_{\text{Nd}}$  at 1850 Ma for samples of the Animikie Group in the Mesabi Range.  $f_{\text{Sm/Nd}}$  is the deviation of Sm/Nd from CI chondrite and  $\epsilon_{\text{Nd}}$  is the deviation of  $^{143}\text{Nd}/^{144}\text{Nd}$  from CI chondrite in parts per 10,000. P = Pokegama Quartzite, B = Biwabik Iron-formation, and V = Virginia Formation. M = Marquette Range Supergroup samples [9]. For additional reference, the fields for late Archean Superior Province rocks [13], early Proterozoic plutonic rocks from central Minnesota [4,5] and Wisconsin [9], and Gunflint Iron-formation from Ontario [14,15] are shown.

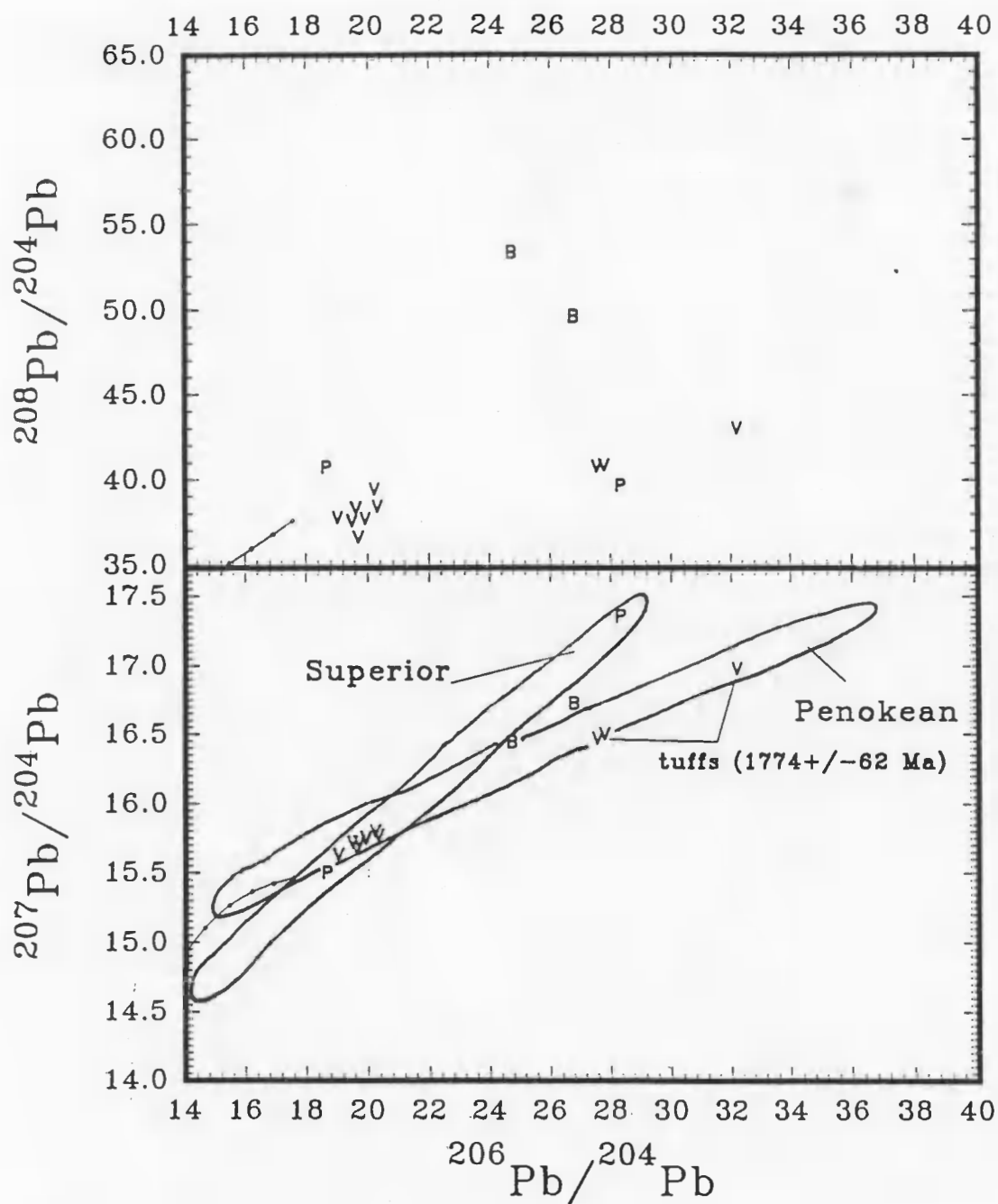


Fig. 2 Pb isotope compositions of samples from the Animikie Group in the Mesabi Range. The same symbols apply as in Fig. 1. a) Plot of  $^{208}\text{Pb}/^{204}\text{Pb}$  vs  $^{206}\text{Pb}/^{204}\text{Pb}$ . Growth curve is  $\mu=8$ ,  $\kappa=4$ , with tics at 100 Ma intervals. b) Plot of  $^{207}\text{Pb}/^{204}\text{Pb}$  vs  $^{206}\text{Pb}/^{204}\text{Pb}$ . Growth curve is  $\mu=8$  with tics at 100 Ma intervals. For reference, fields including feldspar and whole rocks for late Archean late- to post-kinematic plutonic rocks of the Superior Province [16] and early Proterozoic plutonic rocks of central Minnesota [4,5], and feldspar, galena, and whole rocks from both volcanic and plutonic rocks from Wisconsin (WMT) [8] are shown.

## EXPLORATION AND MINING ACTIVITIES OF INDUSTRIAL MINERALS IN NORTHWESTERN ONTARIO

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The "Northwestern Ontario Industrial Minerals Program" was initiated, in 1987, as part of a province-wide strategy to stimulate development of Ontario's industrial mineral resources and related manufacturing industries. The Industrial Minerals Program provides assistance to prospectors and industry by conducting property visits, sample preparation, analyses and discussion relating to the industrial mineral industry.

There are over 50 industrial mineral commodities known to occur within Northwestern Ontario. Current production includes: two quarries producing almost 1,000,000 tons of railway ballast material; two granite dimension stone quarries producing blocks and slabs of pink granite for use as monument and dimension stone; a third dimension stone quarry will start production in April 1992 and produce rough blocks and slabs of green granite; one quartz quarry which produced 17,000 tons of crushed quartz; and one quarry produced 8,000 tons of crushed diabase for use in soil erosion projects.

This poster displays current producers, sites of advanced exploration and high potential areas. Detailed information on all the properties is available from the Resident Geologists' Office in Thunder Bay.

Exploration and prospecting is currently under way to evaluate a number of properties for their dimension stone, garnet, amethyst and graphite potential.

Northwestern Ontario includes the Resident Geologists' Districts of Kenora, Red Lake, Sioux Lookout, Thunder Bay, Beardmore-Geraldton, and Schreiber-Hemlo.

The program is jointly funded by the CANADA-ONTARIO 1991 Northern Ontario Development Agreement (NODA), a subsidiary agreement to the Economic and Regional Development Agreement (ERDA) signed by the Governments of Canada and Ontario.

The project is staffed by Peter Hinz, Geologist, and Robert Lucas, Assistant Geologist.

## **Thermochronologic evidence for post-Penokean unroofing in the Lake Superior region.**

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**Introduction.** Determining the time, amount and nature of unroofing of rocks deeply buried during collision is fundamental to an understanding of the processes of lithospheric deformation. During the past decade, the construction of temperature-time histories has become an increasingly important technique for assessing unroofing histories. Because changes in the cooling history (shown as inflection points on temperature-time curves) are likely to be a reflection of tectonic events, these data are extremely useful for discerning and dating such events as well as for characterizing their thermal significance. Determining the post-collisional cooling history of ancient orogenic roots is commonly difficult due to thermal overprinting associated with younger events. Such has been the case in the Precambrian of Michigan and Wisconsin where 'events' dated at ~1630 Ma, ~1330 Ma, and ~1140 Ma have masked the earlier cooling history of rocks initially buried during the ~1830–1860 Ma Penokean orogeny. Here, we present  $^{40}\text{Ar}/^{39}\text{Ar}$  cooling ages from rocks metamorphosed during the Penokean orogeny in east-central Minnesota, an area apparently affected to a lesser extent by these later events.

Proterozoic rocks in east-central MN lie athwart the Great Lakes tectonic zone, an Archean crustal discontinuity along which alternating extensional and contractional events have occurred throughout the Early and Middle Proterozoic. Denham Formation cover rocks (predominantly quartzite and dolomite interbedded with conglomerate and volcanic rocks) were deposited on Archean quartzofeldspathic basement (the McGrath Gneiss) in an Early Proterozoic (2100–1900 Ma) extensional basin. They were subsequently deformed and metamorphosed to amphibolite facies during the Penokean orogeny (1860–1830 Ma), having reached burial depths in excess of 21–25 km.

**Summary of previous geochronology\*.** Several rock forming 'events' following the Penokean orogeny have been identified in the Lake Superior region. These include the formation of a plutonic-volcanic terrane in south-central and northern WI at ~1760 Ma, intrusion of the Wolf River Batholith at ~1469 Ma, and magmatism associated with the Mid-continent Rift System at ~1100 Ma. In MN, post-orogenic granites yield minimum U-Pb ages of 1770 Ma and U-Pb crystallization ages of  $1812 \pm 9$  Ma. Initial conventional K/Ar and Rb/Sr chronologic data from eastern and central MN were recomputed and summarized in Keighin et al. (1972 Centennial Volume; MN Geol. Surv.). K/Ar biotite and muscovite ages from basement and cover rocks group into ages largely around ~1730 Ma (7 ages ranging from 1670–1770 Ma) and ~1630 Ma (6 ages ranging from 1610–1650 Ma). Rb/Sr dates include errorchron ages of  $1746 \pm 86$  Ma and  $1741 \pm 18$  Ma and biotite ages in the interval of 1750–1740 Ma for the McGrath Gneiss.

There have been several studies using both the Rb/Sr and Ar/Ar systematics in the regionally equivalent rocks of MI and WI. The oldest ages, generally preserved in a belt just south of Mid-continent Rift rocks, are 1692–1750 Ma Rb/Sr biotite ages and one Ar/Ar hornblende plateau age of 1704 Ma. To the south, whole-rock Rb/Sr and Ar/Ar biotite ages are reset in response to a regionally recognized but cryptic event at about 1630 Ma. Younger events superimposed on this regional 1630 Ma imprint, recognized in both Rb/Sr and Ar/Ar systematics, occur at ~1330 Ma and ~1140 Ma.

**Results of this study.** A coarse-grained amphibolite schist was sampled at the type locality of the Denham Formation. Coarse amphibole and finer-grained biotite form a well-developed foliation at this locality, the amphibole commonly containing large inclusions of plagioclase. A biotite separate (DH-MN-4) gives a plateau age of  $1754 \pm 13$  Ma. A hornblende separate from the same sample gives a plateau age of  $1756 \pm 16$  Ma, concordant with the biotite age. These two ages, from minerals with highly discordant closure temperatures (~500°C and ~300°C), indicate rapid cooling roughly 60–100 Ma after metamorphism during the Penokean orogeny.

We observe that of the first 10 increments in the hornblende spectra, four consecutive increments (3–6) give concordant ages of ~1615 Ma and have K/Ca ratios an order of magnitude greater than

those of the plateau increments. In addition, these same four increments, when subject to regression on the isotope-correlation intercept plot, yield a concordant intercept age of  $1615 \pm 9$  Ma with an atmospheric initial  $^{40}\text{Ar}/^{36}\text{Ar}$ . These combined observations lead us to interpret the "mini" plateau age of  $\sim 1615$  Ma as dating the plagioclase inclusions in the hornblende. The younger age is consistent with plagioclase having a lower closure temperature ( $\sim 230^\circ\text{C}$ ) than either biotite or hornblende. These data may indicate that the regional low-grade  $\sim 1630$  Ma event recognized in MI and WI also affected the rocks of east-central MN, although perhaps to a lesser extent.

Muscovite from the McGrath Gneiss (sample DH-MN-6) yields a plateau age of  $1705 \pm 19$  Ma and biotite (sample DH-MN-7) yields a plateau age of  $1702 \pm 12$  Ma. The concordant mica ages indicate rapid cooling (from temperatures above  $350^\circ\text{C}$  to below  $300^\circ\text{C}$ ) of the gneiss at about 1705 Ma.

**Discussion.** Considering the high closure temperature for Ar diffusion in hornblende ( $\sim 500^\circ\text{C}$ ) and apparent lack of intrusions in this region it seems unlikely that the cover rock ages represent thermal resetting, and are therefore interpreted as representing simple cooling. Rapid cooling from temperatures above  $500^\circ\text{C}$  to below  $300^\circ\text{C}$  is a strong indication of tectonically driven uplift. In contrast, rocks cooled during isostatic rebound will have relatively slow uplift rates so that mineral pairs will give measurable age differences.

It has long been observed that continental extension commonly occurs along previously overthickened crust with a characteristic time lag between the end of thrusting and the peak of extension of  $\sim 30$ – $100$  Ma. These generalizations seem to indicate that regions of overthickened crust create characteristics favorable for post-collisional extension. In the Precambrian of MN, we observe that rapid cooling began roughly 60–100 Ma after the Penokean collisional orogen and was coeval with regional rhyolitic volcanism and granite emplacement in MI and WI. Major cooling occurred dominantly in the time-span 1755–1740 Ma as indicated by the 1740–1750 Ma Rb/Sr ages cited above for this region. However, cooling apparently continued until  $\sim 1700$  Ma considering the concordant 1705 Ma basement muscovite and biotite ages presented here as well as the  $\sim 1700$ –1750 Ma Rb/Sr biotite and 1704 Ma hornblende plateau ages in northernmost WI and MI.

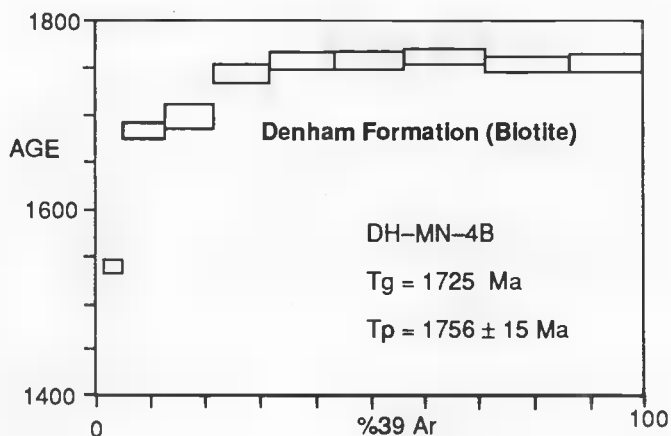
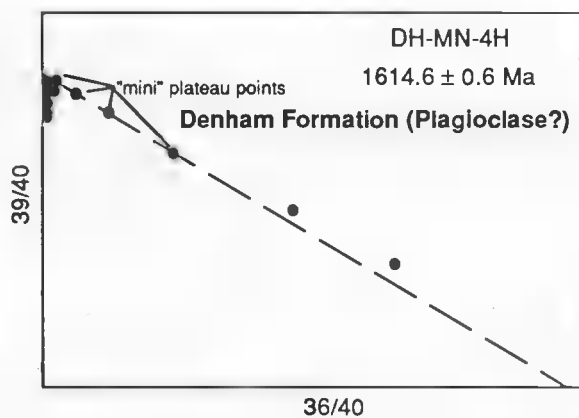
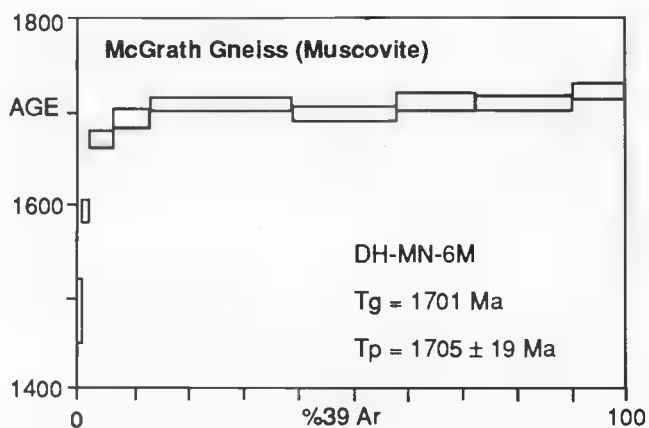
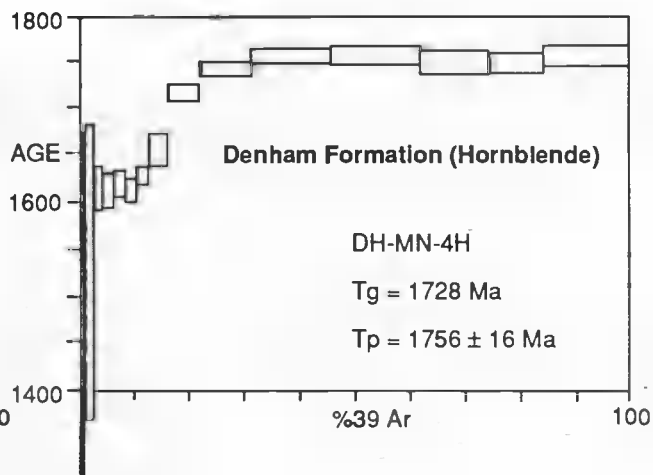
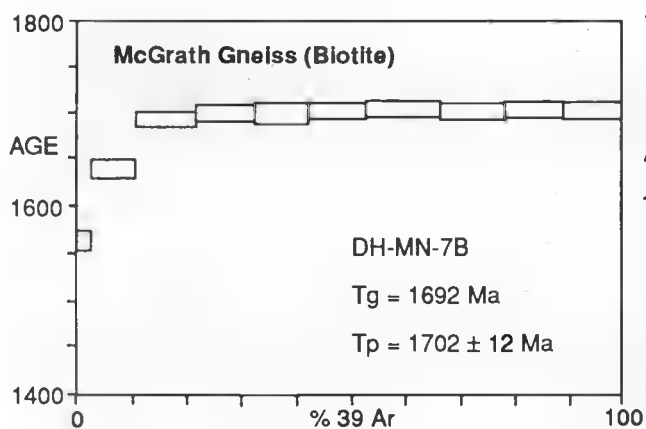
All of these observations are, in general, characteristic of Phanerozoic extensional regimes worldwide. Based on these similarities, we believe these data might best be explained by a major extensional episode in the Lake Superior region at  $\sim 1750$ – $1700$  Ma. The regional extent of this episode has largely been obscured by later disturbances in both Rb/Sr and Ar/Ar systematics in much of MI and WI. The low-grade  $\sim 1630$  Ma event well recognized in those areas may have also affected the rocks of east-central MN (although to a lesser extent) as suggested by the  $1615 \pm 9$  Ma preferred plagioclase age and the  $\sim 1630$  Ma clustering of K/Ar mineral ages.

Structures associated with extensional unroofing of ancient compressional orogenic roots may be difficult to recognize due to localization of deformational features (e.g., detachment faults). The paucity of exposure in this region would also make identification of extensional structures difficult. We do suggest that late-stage anastomosing shear zones which cross-cut the dominant foliation in the McGrath Gneiss might be attributed to extension. Also, a single isolated outcrop at the Denham Formation type locality has upright folds oriented  $\sim 90^\circ$  to the regional east-west orientation perhaps reflecting rotation during extensional unroofing. Detailed structural analysis of recently drilled core samples may ultimately test our explanation of the cooling ages by allowing identification of extensional structures (or lack thereof) associated with tectonic unroofing.

**Conclusion.** Cooling ages provide one method for differentiating between relatively fast, tectonically driven uplift (e.g., via post-collisional extensional unroofing) and slow, isostatic unroofing following cessation of convergence. We suggest that rapid cooling and magmatism 30–100 Ma after burial associated with the Penokean collisional orogeny may reflect a previously unrecognized post-tectonic unroofing event in the Lake Superior region, possibly analogous to that commonly observed in Phanerozoic mobile belts worldwide.

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\* We regret not having room to cite references in this section. We will make them available upon request.



$T_g$  = total gas age     $T_p$  = plateau age

Holm, Holst, and Lux

## ON THE USE OF PALEOCURRENT INDICATORS IN DEFORMED ROCK

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A number of sedimentary structures have long been used as indicators of current direction at the time of deposition of the sediments that contain them. When the deposits are flat-lying and undeformed this is a straightforward process. If there has been post-deposition deformation, including any displacement, rotation, tilting, folding, and finite strain, the deformation history must be known in some detail in order that the beds may be restored to their original position, for any paleocurrent data to be valid. This process can be far from simple.

If read correctly from undeformed rocks, sedimentary structures which are current indicators yield a horizontal vector indicating the direction of current flow. This vector may be deflected from its original position by many types of deformational process. In the general case the deformation history may involve several episodes of deformation, each of which may have included one or more of the processes of displacement, rotation, tilting, folding, and finite strain. To restore the beds to correct original position, a series of deformation inversions needs to be performed. In practice, the necessary information to perform these inversions is almost never completely known.

Finite strain analysis in rocks has progressed a great deal in the last few decades, but still many rocks are not amenable to strain analysis. Even if suitable finite strain data may be recovered, information on strain path, necessary if the current vector is to be restored to correct initial position, has proven to be extremely elusive. Veins and strain-shadow fibers have provided this information in some situations, with results showing evidence of non-coaxial strain histories sufficiently often so that if strain path information is lacking, paleocurrent data may be considered suspect.

If finite strain and strain path data are known, removal of these effects by deformation inversion may still leave the bedding in a position other than original, and effects of folding, tilting, rotation and displacement must also be considered. This is also the starting point for consideration of rocks with negligible finite strain. Ramsay (1961) showed that the effects of strain and folding on sedimentary structures were more profound than had generally been appreciated, and outlined a technique for deformation inversion of folding once effects of finite strain had been removed. This technique involves rotation of the material about an axis perpendicular to plunge direction of measurable folds in the area, until the fold axes are horizontal, and then rotation of the bed in question about the strike to restore to horizontal. This is a relatively straightforward technique, but will only result in a correct interpretation if this procedure is indeed a deformation inversion. In the general case, this will almost certainly not be true.

Paleomagnetic studies in a number of areas have shown fairly large rotations, as much as 140 degrees during displacement deformation. In many of these areas, finite strain is minimal, and the rocks on an outcrop scale appear nearly undeformed. Early episodes of such rotation leave only a magnetic record in the rock, which may be eliminated or rendered effectively undecipherable by later deformation and/or

metamorphism. If paleomagnetic data are not available, one can only assume that no such rotation has taken place when attempting to restore paleocurrent vectors. This often may not be a safe assumption.

Even in areas without such displacement rotations, and with minimal finite strain, complications are certainly possible. In areas of plunging folds with a seemingly simple deformation history, it has been shown, again from paleomagnetic studies, that the technique outlined in Ramsay (1961) is not a correct deformation inversion. Using progressive demagnetization techniques on rocks from an area where there were several periods of magnetic resetting, McClelland Brown (1983) found that the deformation history of a particular fold in the Old Red Sandstone in Pembrokeshire involved marked changes in plunge (both steepening and gentling during deformation), and in plunge direction during fold development, even through nearly 180 degrees (opposite plunge directions) during one stage. Studies such as these show that when information (from paleomagnetic studies) about fold or displacement histories is not available, paleocurrent data should be considered suspect.

In addition to errors in orientation of a single current vector introduced in paleocurrent data from unknown or partially known deformation histories, problems may also arise because of apparent patterns in data sets, which are purely an artifact of the deformation history, and not the original paleocurrent pattern. Depending on the deformation history and the geometrical relationships between bedding, true current direction, and the various deformation components, deformation processes may create an apparent single cluster of paleocurrent vectors, an apparent bimodal, bipolar distribution, or may even spread out to a large degree an original fairly close clustering. As certain of these patterns are generally taken as being indicative of particular environments of deposition, there are obvious dangers involved in placing much faith in studies of paleocurrent patterns in deformed rock where information necessary to perform a complete deformation inversion is not available.

Many studies have shown that deformation histories of deformed, or apparently undeformed rock are much more complex than they appear to be. In general, detailed information on deformation history is not attainable in rocks. In the absence of detailed and complete information on deformation history, paleocurrent data must be considered suspect. Orientation errors introduced by deformation processes may be substantial, and artificial patterns may be introduced to a group of data.

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## Airborne Geophysical Survey of Northwestern Wisconsin.

by

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In 1988, the United States Geological Survey conducted an airborne geophysical survey over northwestern Wisconsin as part of the Great Lakes International Multidisciplinary Program on Crustal Evolution (GLIMPCE) program. The 6000 line-kilometer survey covered portions of Bayfield, Burnette, Douglas, and Washburn counties. The survey flight line direction was north-south, the flight line spacing 800 meters, and the survey altitude 91 meters above ground level. Magnetic and very low frequency (VLF) resistivity data were collected.

The geology of the survey area consists of Precambrian bedrock overlain by glacial deposits. The oldest bedrock units are Middle Keweenawan, Chengwatana volcanic rocks composed of mafic to intermediate lavas and interbedded sedimentary rocks. The Upper Keweenawan, Copper Harbor Conglomerate overlies the volcanic rocks. The youngest bedrock units, the Upper Keweenawan Bayfield Group sandstones, are juxtaposed against the Chengwatana volcanic rocks by the Douglas fault. Late Wisconsin to Holocene glacial deposits consist of alluvium, peat, lake silt, clay, ice-contact and outwash sand and gravel, and clayey to loamy ground moraine and till. These glacial deposits range from less than 1 to greater than 100 feet thick.

The most obvious features on the aeromagnetic map (Figure 1) are related to the Ashland-Lake Superior syncline. The axis of the syncline strikes northeasterly through the center of the survey area. The narrow, northeasterly-trending linear anomalies are produced by dipping volcanic rocks, upturned along the northwest and southeast limbs of the syncline. The Copper Harbor Conglomerate occupies the center of the syncline where a relatively deep and flat-lying, magnetic basement produces the broad-gradient magnetic anomaly. In the northern portion of the map, the Douglas fault, has brought the relatively non-magnetic Bayfield Group sandstones in contact with the older, southeast-dipping, magnetic volcanic rocks. In the extreme southern portion of the survey area, the low-amplitude magnetic anomaly is thought to be caused by deep magnetic basement below thick sedimentary rocks.

Unlike the aeromagnetic map, the VLF apparent resistivity map (Figure 2) reflects a combination of topographic, bedrock and surficial geologic features. Across the northern portion of the survey area low resistivities are produced by conductive lake sediments deposited in the topographically-low region between Lake Superior and the Douglas fault. South of the Douglas fault sand, gravel, and moraine deposits produce the intermediate resistivities that cover the majority of the survey area. Small conductive anomalies result from deposits of clay and peat in lakes and shallow depressions. The highly resistive zones are produced by thick, clay-free sand and gravel deposited as outwash or ice-contact deposits. Subtle northeast-striking features observed throughout the survey area reflect the direction and resultant deposits of southwesterly glacial advances and the influence of underlying bedrock features.

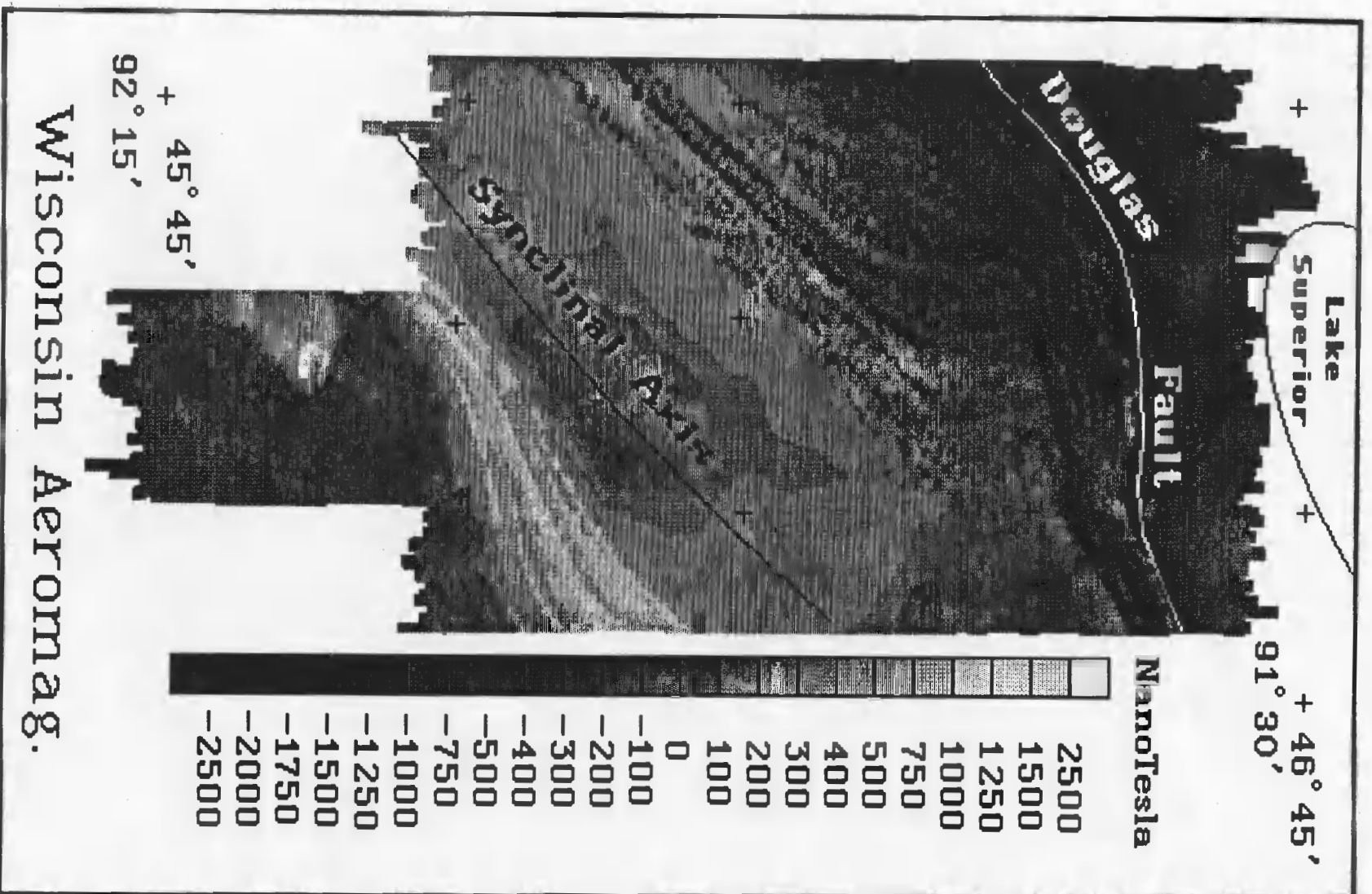


**Figure 1.** Gray-scale aeromagnetic map of the northwestern Wisconsin survey area. Lighter shades of gray represent magnetic field highs, darker shades of gray represent magnetic field lows. Narrow, linear, northeast-trending anomalies are produced by dipping Chengwatana volcanic rocks. The broad-gradient anomaly in the center of the map is produced by deep magnetic basement below the Copper Harbor Conglomerate.

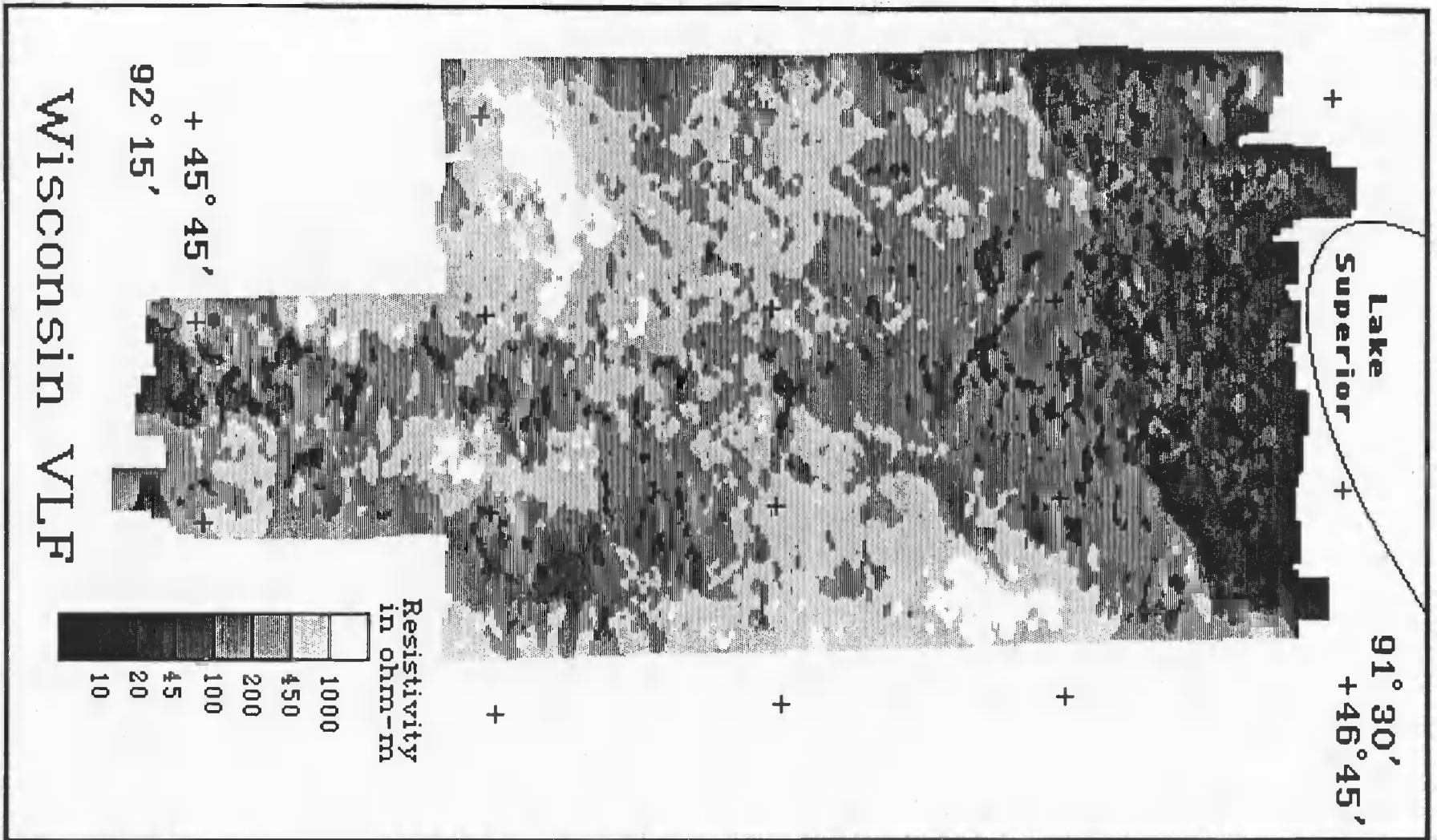


Figure 2. Gray-scale VLF apparent resistivity map of the northwestern Wisconsin survey area. Light shades of gray represent high resistivity areas, dark shades of gray represent low resistivity areas. Conductive lake sediments produce the low resistivity terrain across the northern portion of the survey area. Sand, gravel and moraine deposits produce the intermediate resistivities that cover the majority of the survey area. High resistivity areas are produced by thick deposits of clay-free sand and gravel.

Magnetic studies of the Dresser-St. Croix Falls Area, Polk County, Wisconsin.

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The ground magnetic study by Reich (1989) and the paleomagnetic study by Feeney (1990) have been incorporated and compared to the bedrock map in the Dresser-St. Croix Falls area by Cordua (1989). Paleomagnetic results from 11 locations give five normal sites, four reversed sites and two mixed sites. The pole positions when corrected for dip give magnetic directions close to either the North Shore volcanics or the Gargantua volcanics. The remanent intensities and susceptibilities are typically large, with ratios of the remanent to induced components ranging from .4 to 1.4. This implies that remanent intensities will strongly influence land magnetic surveys and interpretations. The land magnetic surveys by Reich (1989) showed a significant number of anomalies about 1/4 to 1/2 mile wide and 300.0 gamma to 500.0 gamma in intensity. Preliminary modelling suggests these features are caused by magnetic characteristics of individual flows rather than by bedrock topography as originally proposed. In addition, the combined rock magnetic and land magnetic studies are reasonably consistent with the mapping by Cordua (1989) and could be used to extend the mapping in areas covered by glacial drift.

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## MAGNETIC AND PETROGRAPHIC DETECTION OF HEAT TREATMENT IN GUNFLINT CHERT

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In the Thunder Bay, Ontario area, "taconite" was the material of choice for the manufacture of stone implements during the late Paleo-Indian period ca. 9000 b.p. (Fox, 1975; Dawson, 1983). The "taconite" is an iron-bearing chert, which occurs as stratabound nodules and lenses in calcareous and siliceous siltstones of the local Gunflint Formation. Studies have indicated that heat treatment of siliceous materials improves their flaking characteristics, both in ethnographic (Hester, 1972; Mandeville, 1973) and experimental investigations (Crabtree and Butler, 1964, Mandeville and Flenniken, 1973; Flenniken and Garrison, 1975). The possibility that heat treatment was employed in the Thunder Bay area technology has been suggested (Fox, 1975; Dawson, 1983), and a method of detection of such treatment is important in the continuing study of this culture.

"Taconite" specimens from three bedrock outcrops in the Thunder Bay area were heated at 425 and 500°C for 2½ hr. and allowed to cool to room temperature. Comparison to unheated specimens revealed some color differences attributable to heating; however, the mesoscopic and microscopic heterogeneity of the specimens did not permit mineralogical reflectance and microhardness techniques to be usefully employed. Optical microscopy using transmitted and reflected light on polished thin sections revealed distinctive differences in most specimens. The most pronounced effect of heating was a loss of organic carbon, resulting in bleaching of most carbon-rich specimens and migration of carbon from inclusions to grain boundaries and cracks. Decarbonation of siderite with production of hematite is also significant in carbonate-rich specimens.

Non-destructive measurement of magnetic properties revealed that magnetic susceptibility, saturation isothermal remanent magnetization and magnetic hysteresis parameters all changed as a result of heating. Because the natural remanent magnetism (NRM) of the Gunflint cherts is highly variable and unstable, this property is not a useful parameter for distinguishing heated from unheated material although it has been used in archeological work in Europe. Also, mechanical action and shock in the manufacture and use of implements would perturb and alter the NRM. We took ten specimens of the cherts and broke them in two. One part was kept as a control sample and the other half heated. In this way, the susceptibility was measured before and after heating as well as the hysteresis properties. Instead of using the natural magnetization of the samples, we compared their ability to retain a large (saturation) magnetization in an inducing field of 950 mT (9500 oersteds). This isothermal remanent magnetization (IRM) increased greatly as a result of heating as did the susceptibility. These parameters alone allow one to distinguish between cherts which had been heated and the unheated, control specimens.

Hysteresis loops in unheated materials are frequently "wasp-waisted" because of the presence of two magnetic minerals (Jackson *et al.*, 1990). Heated specimens lose "wasp-waistedness", although the changes in hysteresis behavior are variable.

Petrographic and magnetic studies of Gunflint cherts appear to provide a means by which heat treatment in the manufacture of stone implements may be detected. Magnetic methods are particularly attractive, as they are non-destructive so long as an artifact under investigation will fit the constraints imposed by sample holders and instruments. Moreover, the magnetic methods will be applicable to samples such as normal chert or flint with much lower iron contents than the specimens we need.

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## **ALTERATION, FLUID INCLUSION, STABLE ISOTOPIC AND STRUCTURAL STUDIES OF THE RABBIT MOUNTAIN SILVER MINE, THUNDER BAY DISTRICT, ONTARIO**

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The Rabbit Mountain Mine was the first discovered of a number of silver mines lying well inland of Lake Superior. Total production from the mine amounted to approximately 50,000 oz. in the period 1882-1893, during which the mine operated sporadically (Tanton, 1931). Although production was modest, the discovery of the Rabbit Mountain Mine led to additional significant discoveries, e.g. Silver Mountain, Beaver, Badger and Porcupine, extending silver mining in the Thunder Bay District, following depletion and closure of the famous Silver Islet Mine. Sporadic activities subsequent to the main period of mining did not yield additional production; however, in 1967-1968, dewatering permitted underground sampling and mapping.

The deposit consists of two veins, no. 1 vein, carrying most of the ore, and no. 2 vein, essentially a barren system with trace quantities of sulfide minerals. Both veins strike at about 230° with dips of 50 to 70° northwest. The no. 1 vein varies from 1 to 3 m in thickness, and no. 2 vein, outcropping about 100 northwest of no. 1 vein, is about 1 m thick. A few minor veins with the same attitudes outcrop between no. 1 vein and no. 2 vein. The veins are in Rove Formation shales in faults that offset capping Logan diabase sills. Brecciation and recementation of earlier vein deposits by later deposits is observable in the field.

The ores contain acanthite (pseudomorphous after argentite), native silver, sphalerite, galena, pyrite and chalcopyrite. Gangue consists of quartz, including a vug-filling amethystine variety, calcite and green and purple fluorite. Barite was reported by Tanton (1931) and earlier workers, but was not encountered in this study.

The veins and their narrow alteration zones (typically 10 cm wide) cut the zone of contact metamorphosed shale, which developed microscopic-sized porphyroblasts of andalusite in response to intrusion of the diabase sill, ca. 13 m thick. The veins pinch down to a few centimetres width in the diabase and wallrock alteration is negligible. The alteration zones in the shales are often delineated by bleaching owing to a loss of carbon, which is present in the unaltered shale. The only mineralogical change noted is alteration of illite(1M) to illite(2M). Studies of trace content in uniformly spaced samples taken perpendicular to no. 2 vein indicate apparent depletion in Cu and possible depletion in As in a zone extending 5 ft from the vein. Within this zone Zn, Pb, Co, Ni and Ag exhibit apparent enrichment, and, although concentrations of Hg in most cases are below the detection limit of the atomic absorption spectroscopy technique employed, within 2 ft. of the vein clear enrichment in Hg is present.

Fluid inclusions in calcite, quartz, sphalerite and purple fluorite indicate the presence of two episodes of ore deposition separated by a period of cooling, a pattern common to all

productive silver mines of the inland area (Jennings, 1986). Early calcite yielded homogenization temperatures ranging from 125 to 65°C, whereas post-fracture calcite homogenization temperatures lay in the 90-100°C range, sphalerite in the 80-115°C range and one purple fluorite yielded 308.5°C as compared to 99.7°C in another. Two adjacent inclusions in calcite homogenized to liquid and vapour at ca. 100°C, indicating boiling at near surface depths during position. Final melting temperatures of -15.7 and -15.0°C, corresponding to 19.4 and 18.8 equiv. wt.% NaCl, respectively, were determined. Initial melting temperatures in other deposits suggest NaCl-CaCl<sub>2</sub> or CaCl<sub>2</sub> aqueous systems (Jennings, 1986), -50.6 and -35.6°C were obtained from the Rabbit Mountain sphalerite specimens. The former is in agreement with the eutectic for NaCl-CaCl<sub>2</sub>-H<sub>2</sub>O, but the latter temperature is difficult to interpret, but may reflect the effect of dissolved CO<sub>2</sub> on the NaCl-CaCl<sub>2</sub>-H<sub>2</sub>O system. Daughter minerals were not observed in fluid inclusions from Rabbit Mountain specimens.

Sulfur isotopic analyses yielded  $\delta^{34}\text{S} = -1.2, + 3.5, + 9.3$  and  $+ 9.9$  ‰ in sphalerite and a galena grain paired with the  $+ 3.5$  ‰ sphalerite gave  $\delta^{34}\text{S} = -9.3$  ‰. The wide variation in  $\delta^{34}\text{S}$  in sphalerite is suggestive of a lack of isotopic equilibrium, possibly as a result of precipitation from a solution undergoing oxidation. The isotopic temperature from the sphalerite-galena pair is -35.6°C, an unreasonably low figure probably also indicating sequential deposition from a solution undergoing oxidation.

The results lead to the following conclusions:

1. Ores were deposited at low pressure from moderately saline solutions, which experienced sporadic boiling.
2. The lack of isotopic equilibrium among sulfides and the mild nature of wallrock alteration suggest relatively rapid deposition.
3. Most metallic components of veins as well as Ni, Co and Hg, found in minerals elsewhere in the district (Franklin *et al.*, 1986), seem to have been added to wallrock alteration zones from the ore-depositing solutions. Cu and As, as well as carbon, were depleted in alteration zones.
4. The deposition of ores was a pulsatory process in which thermal highs were separated by a period of cooling and fracturing.

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## THE EARLY PROTEROZOIC EMPEROR VOLCANIC COMPLEX: IMPLICATIONS FOR THE GEOLOGY OF THE EASTERN GOGEBIC DISTRICT, NORTHERN MICHIGAN

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The Emperor Volcanic Complex constitutes a thick pile of Early Proterozoic volcanic rocks and sills in the sedimentary sequence on the eastern Gogebic range. Except for a number of diabase dikes and sills, igneous rocks are scarce on the western Gogebic range. However, igneous rocks are abundant east of Wakefield, Mich., where they reach a thickness of at least 2,000 m. Although the presence of volcanic rocks on the eastern Gogebic range has been known for over 100 years (Irving and Van Hise, 1892), few studies have been undertaken on these rocks. Irving and Van Hise (1892) stated that the volcanic rocks are interbedded with the Ironwood Iron formation, an interpretation substantiated by subsequent exploration drilling for iron ore in the area.

Mapping by Trent (1973) documented the distribution of igneous rocks and showed some of the lithologies present. Dann (1978) showed that the volcanic rocks range in composition from basalt to dacite and that they have been metamorphosed to prehnite-pumpellyite or to lower greenschist facies. Trace element studies by Schulz (Sims and others, 1990) indicate that the volcanic rocks are bimodal rift-related tholeiites and rhyolite.

Geologic mapping in 1991 by LaBerge and J. S. Klasner indicates that the Emperor Volcanic Complex consists of a variety of subaqueous mafic and felsic volcanic rocks and sills. Mafic rocks include sills, pillowed and massive flows--some with columnar jointing, and extensive hyaloclastites and pillow breccias. Felsic rocks include massive felsite breccias, lithic tuffs, hyaloclastites, and breccia-hyaloclastite debris flows. Kokelaar (1986) states that hyaloclastites form mainly in water less than 200 m deep and are more abundant in shallower water. The abundance of hyaloclastites (Figure 1) in the Emperor volcanics, therefore, suggests extrusion in shallow water. Shallow water deposition is further indicated by thin interbeds of oolitic iron formation.

The Emperor volcanic rocks form a wedge within the Ironwood Iron formation that thickens eastward from Wakefield, Mich. Trent's mapping (1973) shows that the formations are truncated by major faults (the Presque Isle Fault and the Sunday Lake Fault) between Wakefield and Mareniso, Mich.

The distribution of volcanic rocks, the abundance of hyaloclastites, and interbedded oolitic iron formation indicate that the Emperor Volcanic Complex formed in shallow water in a basin subsiding markedly to the east during iron formation deposition. Truncation of the formation along faults may be a primary feature. This suggests deposition in a half graben, perhaps during continental rifting (Figure 2). Deformation during the Penokean Orogeny resulted in thrusting (Klasner and others, 1991) to produce the Presque Isle and Sunday Lake Faults and the present distribution of rocks. Rotation of the district during Keweenawan tilting produced the present map pattern.

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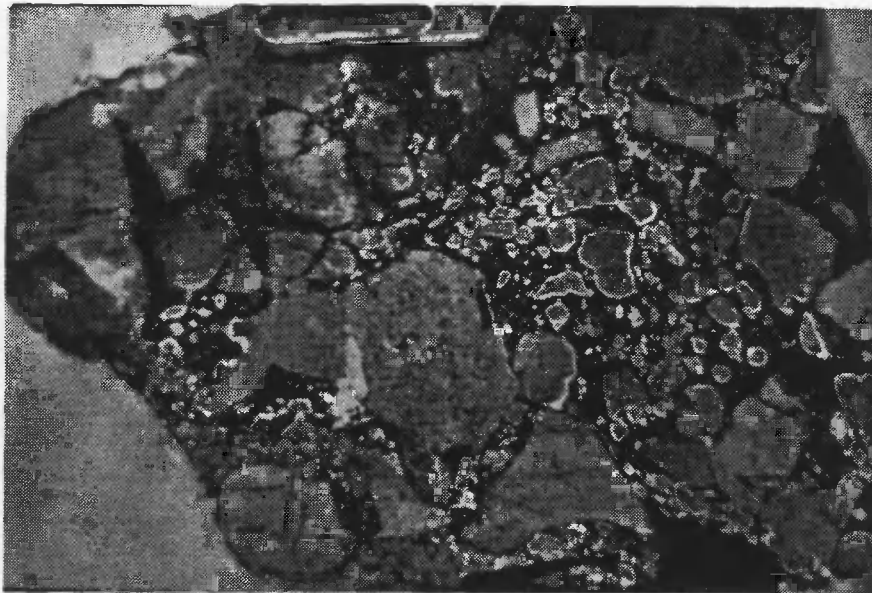


Figure 1. Debris flow from the Emperor volcanics. Larger felsite clasts (gray) in a fine hyaloclastite matrix. Paper clip is 3 cm.

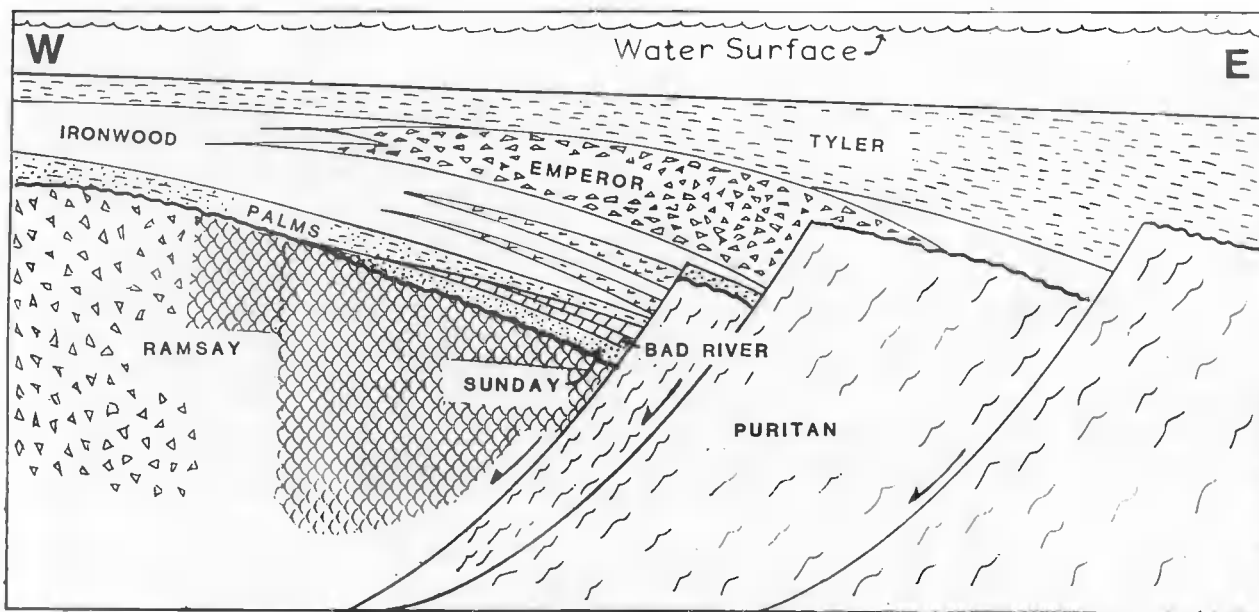


Figure 2a. Diagram showing hypothetical setting of the Emperor Volcanics and sills formed during subsidence of a half graben that deepens to the east.

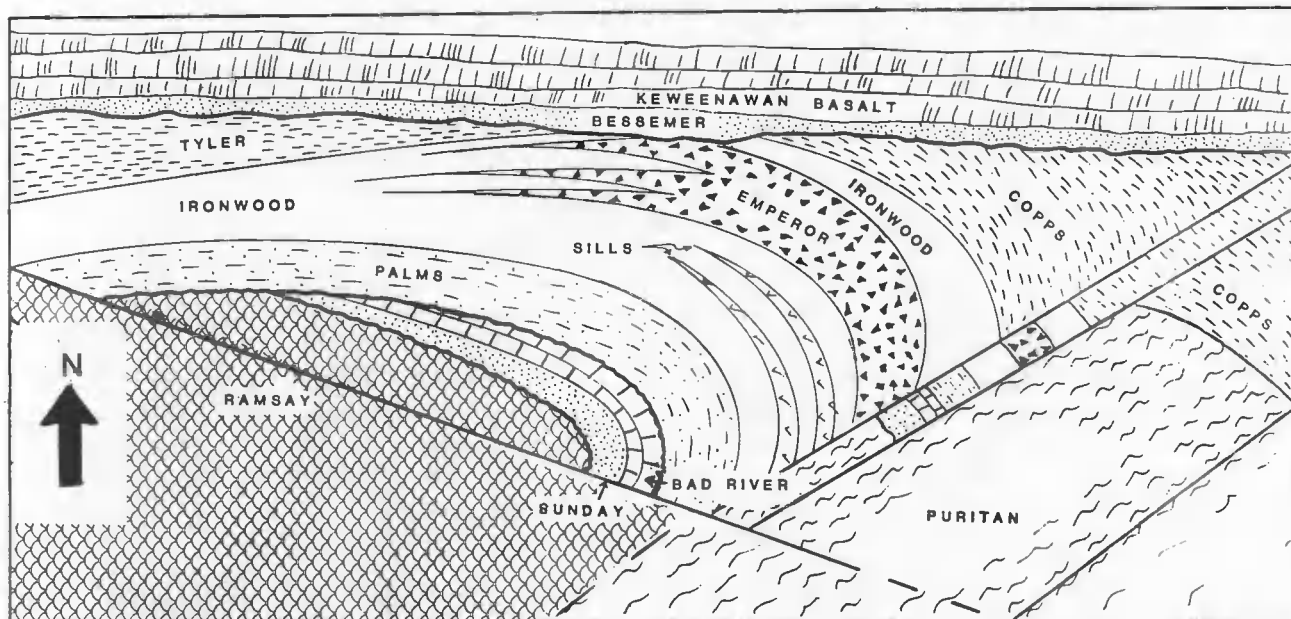


Figure 2b. Simplified sketch map showing relationships of rocks on the eastern Gogebic range. Note that Emperor volcanics and sills are truncated by major faults.

THE CHEMISTRY AND PETROGRAPHY OF MAFIC ROCKS FROM THE EARLY PROTEROZOIC EMPEROR VOLCANIC COMPLEX NEAR MARINESCO, MICHIGAN

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The Emperor Volcanic Complex (EVC) is an Early Proterozoic sequence of mafic and felsic rocks located in the eastern Gogebic Range. A portion of the EVC crops out near Marinesco, Michigan as massive basalts, pillow basalts, and hyaloclastites. The purpose of this study was to characterize the basalts and hyaloclastites petrographically and chemically in order to make inferences regarding the formation and alteration of these rocks.

The outcrop area of this study is located approximately 10 km north of Marinesco, Michigan and encompasses an area approximately 600m by 300m. The outcrop exposes pillow basalts that contain quench cracks and alteration rims. Pillows range in size from 0.1m to 2m. Hyaloclastite, which forms as the result of the interaction of molten rock with seawater or saturated sediments, varies greatly in texture. Fragments produced through this interaction vary in size from a few mm to .5m. Some fragments contain alteration rims that are similar to pillow rinds. Some pillows included in the hyaloclastite appear virtually unaltered while others are highly fractured and altered.

Petrographic analysis reveals that the various mafic rocks are characterized by similar mineral assemblages including epidote, plagioclase, and chlorite, with lesser amounts of calcite, quartz, and amphibole. Textures are variable. Massive and pillowed basalts are primarily composed of subhedral to euhedral mostly fine-grained plagioclase, some euhedral epidote, chlorite, calcite, actinolite, and sporadic pockets of quartz. Rinds on pillows are comprised mainly of plagioclase, some chlorite and epidote, and vein fillings of recrystallized quartz. The hyaloclastite is composed of angular basalt fragments similar in texture to the massive basalt in a coarse to fine-grained matrix that is composed mainly of epidote, chlorite, and quartz. Epidote is medium to coarse-grained and in many samples epidote "flowerettes" are present. The chlorite is mostly amorphous. The quartz is usually fine-medium grained and recrystallized. Some flow structures occur around the basalt fragments.

Preliminary chemical data indicates that the hyaloclastites are similar in composition to the massive basalts.  $\text{SiO}_2$  ranges from 57.2% - 63.6%, MgO varies from 2.8% - 6.3%, Cr varies from 51ppm - 63ppm and Cu varies from 10ppm - 40ppm. Chemical composition of pillow rinds tend to be lower in silica (54.4%) and higher in Cu (49ppm).

The abundance of pillow lavas and hyaloclastites suggests that extrusion onto the seafloor or shallow intrusion into water saturated sediments occurred. The quenching of basaltic lava during eruption/intrusion resulted in the formation of hyaloclastites. Chemically, the basaltic fragments within the hyaloclastites show no greater degree of alteration than the basalts from which the fragments were derived, with the exception of the alteration rims that surround individual fragments.

## MAGNETITE OCTAHEDRA IN PILLOW BASALT NEAR WAWA, ONTARIO

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Octahedral magnetite crystals in Archean pillow basalt found south of the Hwy. 101 and Lucy Pit Road intersection near the east end of Wawa Lake have interested numerous geologists since they were noted by Ronald Sage (Precambrian Geologist, Ontario Geological Survey) several years ago. Questions related to these crystals include: (1) are they of igneous or metamorphic origin; (2) are the crystals evidence bearing on the origin of the numerous iron formations in the region; and (3) given that pillow basalt is voluminous in the Michipicoten greenstone belt, why are the crystals confined to the rather small area southeast of Wawa Lake?

Field studies by the author and Ronald Sage have shown that the magnetite octahedra are confined to an area of about 1 km<sup>2</sup>. There is no recognizable correlation with pillow selvages, interiors, amygdaloidal zones, or stratigraphic horizons; less commonly magnetite crystals are present in massive basalt flows. The magnetite crystals occur randomly through various pillowed and massive flows.

Petrographically, the magnetite crystals cut across the relict ophitic/subophitic texture of the basalt (now albite, actinolite, epidote, chlorite, carbonate +/-pyrite, hematite). Preliminary reflected light examination suggests that the magnetite is relatively pure and does not show exsolution or exsolution/oxidation.

The above evidence shows the magnetite octahedra to be of metamorphic origin; presumably the crystals were generated during greenschist facies metamorphism of the greenstone belt. Frost (1991) states that metamorphic development of magnetite in metabasites is somewhat unusual, especially in iron carbonate-rich environments such as the ankerite-siderite rich Michipicoten greenstone belt in the vicinity of Wawa. One can conclude that the isolated area of magnetite porphyroblasts was not subjected to the complete carbonate "soaking" which affected most of the greenstone belt in the Wawa district; the lesser degree of carbonation kept the oxygen fugacity low enough to allow magnetite to crystallization.

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THERMAL MODELING AND ILLITE/SMECTITE GEOTHERMOMETRY  
OF THE PRECAMBRIAN ORONTO GROUP, WISCONSIN AND MICHIGAN

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The thermal history of Oronto Group sediments in the White Pine-Iron River syncline area has been estimated using a combination of illite/smectite (I/S) geothermometry, organic thermal maturity indicators, and one dimensional thermal modeling. Clay and organic maturity data are used to constrain the thermal modeling, which requires estimation of heat flow (including temporal changes in heat flow), time of deposition and erosion of sedimentary rocks, and lithology-dependent thermal properties. The model outputs the time-temperature history and time-temperature indices (TTI) for specified positions within the rock column, and estimates I/S expandability using Waples (1980, AAPG Bull., v. 64, p. 619) correlation between expandability and TTI. Model results most closely match data when the sediments are exposed to a thermal pulse starting at 1115 Ma, peaking between 1105 Ma and 1090 Ma, and ending by 1080 Ma, producing a heating cycle of roughly 35 Ma duration and maximum temperatures at the level of the Nonesuch Formation of 110-125°C. Plausible total thickness for the Freda Sandstone range from 4 to 6 Km.

Illite/smectite geothermometry (modified from Pollastro, 1990, SEPM Spec. Pub.) has been carried out on clays from the Nonesuch and Freda using core from drill holes in Wisconsin near the Michigan border (DO-14, DO-5), from the White Pine-Iron River syncline area (WP and WPB-1, respectively, as well as samples from the mine itself), and from a series of drill holes extending northeast to the vicinity of Trimountain, MI. Expandabilities in the Nonesuch Formation range from a maximum of 25% smectite (R1 ordered) in the Iron River Syncline area to values of <15% smectite (>R1 ordered) in Wisconsin and <5% smectite (>R1 ordered) at White Pine. To the northeast expandabilities decrease to trace percentages, and in the vicinity of Winona pure illite dominates the Nonesuch Formation. Application of I/S geothermometry indicates maximum temperatures in the Nonesuch of approximately 115°C in the Iron River syncline, 140°C in Wisconsin, 160°C at White Pine, and 190°C near Winona. The most reliable temperature in the smectite to illite sequence is that of the change in ordering from R0 to R1 at 100°C. Using just this temperature constraint, temperatures were well above 100°C everywhere in

the Nonesuch Formation, and 100°C was reached at distances above the Freda-Nonesuch contact of at least 300 m at White Pine and 1120 m at Winona. The data indicate a general increase in temperature northeast toward the Keweenaw Peninsula native copper district. The data also confirms organic thermal maturity results that indicate maturities were higher in the White Pine area relative to the Iron River syncline area and increase westward into Wisconsin from the area of the syncline.

The I/S results may also be used to estimate geothermal gradients in the drill holes. In the Winona area, a gradient of 55°C/Km is estimated, a value identical to the average gradient in the modern rift now forming the Salton Trough in California. Higher geothermal gradients are suggested in the White Pine area, which, coupled with lower I/S temperatures imply a decrease in the thickness of the Freda Sandstone to the west. If true, this supports a Freda depocenter possibly off the Keweenaw Peninsula and in turn suggests deeper erosion of rocks of the Keweenaw Peninsula due to an increase in vertical displacement along the Keweenaw fault from Wisconsin to the Keweenaw Peninsula. There may be a relationship between deeper burial near the depocenter off the Keweenaw Peninsula and native copper deposits.

The results of clay expandabilities and geothermometry in the Wisconsin wells are anomalous. While both expandabilities and temperature estimates in the Nonesuch Formation are reasonable and consistent with results further east, the change in expandability with depth in the Freda Sandstone there is not. The transition from >80% R0 smectite to <20% R1 smectite takes place over a depth interval of <125 m, a very abrupt transition relative to I/S versus depth profiles from elsewhere. In addition, both the highly expandable smectite and minor amounts of kaolinite in the shallower Freda are very poorly crystalline. Pollastro and Barker (1986, SEPM Spec. Pub. 38). investigated a well with a similar expandability profile that had undergone erosion and noted that the abrupt transition took place at the top of overpressuring. The abruptness of the clay transformation, coupled with the poor crystallinity of the shallow clays, suggests retrograde alteration of clays in the Freda Sandstone after diagenesis by circulating low temperature waters, perhaps during deposition of Bayfield Group sediments. The fact that clays in the Nonesuch in the same wells appear to have preserved their diagenetic character in turn indicates that the Nonesuch Formation here is a permeability barrier. It is also quite reasonable to assume that the Nonesuch Formation, during diagenesis, might mark the depth at which fluid pressures first exceeded hydrostatic pressures.

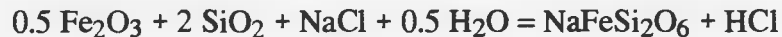
## ACMITE IN THE TROMMALD FORMATION OF THE CUYUNA IRON RANGE: REVISITED

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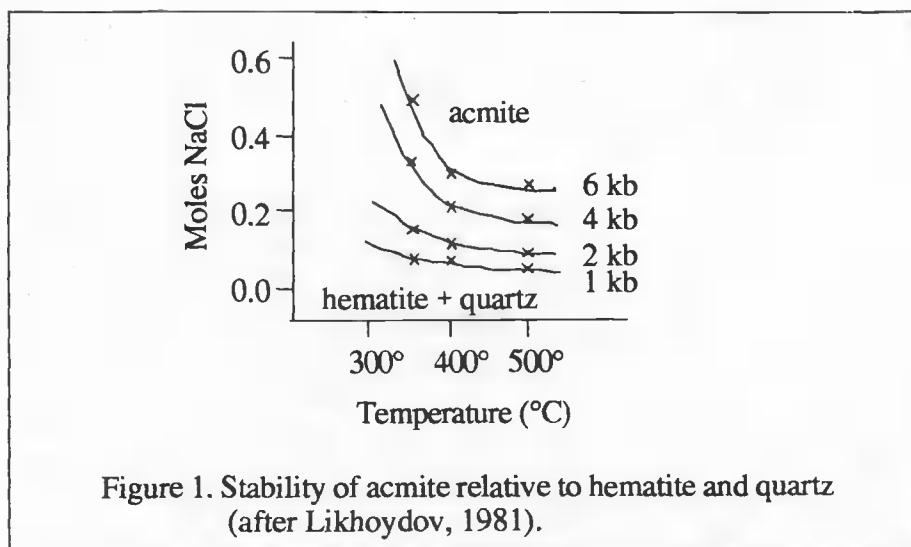
In the process of reevaluating possible protoliths for the ferromanganese ores of the Cuyuna North range, we rediscovered the unusual sodic pyroxene acmite,  $\text{NaFeSi}_2\text{O}_6$ , that was first described from the Trommald Formation by Grout (1946). Discovery occurred in a core obtained from the Merritt Number 2 mine (Sec. 33, T.47N.R29W) where two kinds of acmite were recognized; one a tea-green variety that occurs in small crosscutting veins and a second tan to brown variety that occurs as disseminated grains in granules and as core grains in oolitic structures purportedly rimmed by hematite and chert. The two acmite varieties was concentrated in a layer some 7.5 m (25 feet) thick that forms a marker bed in the Merritt Number 2 and Ferro Mines. Both mines produced appreciable quantities of ferromanganese ore averaging 12-14 percent Mn. Therefore it seems likely that the origin of the acmite is significant to a better understanding of the origin of the protoliths to the ferromanganiferous ores.

This investigation focuses on compositional and textural relationships of acmite from several different settings. Much of the acmite occurs as fine-grained, tan to brown material in beds or lenses, with sharp contacts between it and the surrounding rock. However in some situations, contacts are irregular and the acmite is clearly secondary. Acmite also occurs as rounded clasts of either coarse crystals, fine material, or as intergrowths with rhodonite ( $\text{MnSiO}_3$ ). These clasts commonly form core grains in oolitic or pisolitic-like structures where the rim material is either hematite or red-colored, cryptocrystalline acmite. However these grains may not be of ordinary sedimentary origin. Several grains show that the cores are actually acmite crystals growing into a center filled with quartz. Other core grains have secondary acmite growths forming variously shaped appendages on the rounded clasts. Acmite also occurs as zoned rims around other kinds of core grains, including Mn-oxides, quartz, rhodonite, and rhodochrosite. The veined acmite described by Grout (1946) is clearly secondary in nature, whereas many of the other textural relationships appear to be primary sedimentary structures. Compositionally, the acmite varies from approximately 80 to 95 mole%  $\text{NaFeSi}_2\text{O}_6$ ; the remainder is made up of other pyroxene components, containing Ca and Mn.

Acmite/aegirine is a fairly common mineral series in sodium-rich igneous rocks, but it also occurs in blueschist-facies metamorphic rocks. The Trommald Formation, however, is a formation of sedimentary rocks that has been metamorphosed no higher than the upper greenschist facies. Thus Grout (1946) suggested that the acmite formed by a reaction between sodium-rich hypogene hydrothermal solutions and a mixture of chert and hematite. Experimental work has shown that acmite/aegirine can form over a wide range of P-T conditions. The upper stability limit of acmite as defined by its solidus occurs over a temperature range of 780°-1200°C in the pressure interval 1 to 10 kbars (Bailey, 1969). The lower stability limit for acmite has been investigated by Likhoydov (1981). He has shown that acmite/aegirine can form according to the reaction:



where the temperature of the reaction is very dependent on the pressure and on the concentration of NaCl in the solution (Fig. 1). Given that sea water contains about 0.5 molar NaCl, Likhoydov's data suggest that acmite could easily form at temperatures of 200°C or less at very low pressures. Acmite of possible authigenic origin have also been reported from the Green River Formation of Wyoming and Utah (Milton and Eugster, 1959), and from Caithness, Scotland (Fortey and Michie, 1978).



This project is supported by the U.S. Bureau of Mines—Selective Mining in Minnesota.

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## ABSTRACT

### Accessing the Anaconda Geological Documents Collection Minnesota - Wisconsin - Michigan - Ontario

Daniel N. Miller, Jr.<sup>1</sup>

The International Archive of Economic Geology is a unique public repository and research facility available to the mining industry and researchers. The central part of the archive is the Anaconda Geological Documents Collection made available to the University in 1987 by ARCO Coal Company. It consists of 1.8 million documents and represents more than 90 years of corporate records and files covering mineral exploration and mine development activities throughout much of the United States and 110 foreign countries. Others have described this collection as the largest and most significant body of economic geologic data in the world.

The Anaconda Collection is a wealth of original unpublished geological material compiled by mining geologists, engineers, and specialists who followed the original policies prescribed by Reno H. Sales. Sales established the geological department for Anaconda and was their Chief Geologist from 1905 until he retired in 1954. Throughout his career, he proved to be a highly competent administrator, organizer, and long-range planner who expected the staff to employ their highest level of professional competence at all times. His direct, systematic, analytical, and scientific approach to exploration played a major role in the company's efforts toward data gathering and record keeping, coupled with peer review of all work performed. As a result, Anaconda's files grew over the years and became the envy of the industry.

Today, the Anaconda Geological Documents Collection consists of codified material on more than 18,000 geological reports, with over 5,500 documents and 6,500 maps on mining prospects alone. There are more than 10,000 documents with geologic, geochemical, geophysical, drilling, assay, and commodity data analyses and many thousands of letters, memoranda and other documents: annual reports, smelter data, surface and underground maps of all kinds, engineering drawings and mine plans, aerial photographs, remotely sensed imagery, and even thin sections of rock specimens.

All of the material is systematically indexed on a computer data base and readily retrievable by country, state or province, county, project/mine name, mining district, commodity, author, and date. Inventory searches offer initial cross-indexed access to the 1.8 million individual documents. In most instances, print-outs of inventory searches tailored to specific inquiries can be developed quickly for individual users. The average retrieval time for documents is two and one-half minutes.

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University of Wyoming, Laramie

This collection is maintained and operated entirely as a self-supported system through user fees and contributions from the minerals industry. Neither state nor university funds are involved. Researchers may select any one of the five categories of membership in order to have direct access to the files. Each membership level carries with it certain privileges and restrictions. Separate charges are made for all reproductions ordered. Due to limitations on work space, access to the collection is by appointment only, and users should call at least a week in advance to reserve research space. The facilities are open to the public from 8 a.m. to 5 p.m., Monday through Friday. Special arrangements to work on the weekend can be made in some cases. Members may also place orders for reproductions by telephone.

Presently, this archive is handling between 45 and 50 sustaining client memberships that are primarily corporations, companies, and consultants directly involved in mineral exploration. In most cases, rapid access to the information saves companies and individual consultants time and money. The other key item is that there is information available here that is no longer available from any other source.

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|----------------|---------|-----------|-------|-----------|
|                | Files   | Documents | Files | Documents |
| Michigan       | 42      | 87        | 6     | 36        |
| Minnesota      | 42      | 77        | 10    | 21        |
| Ontario        | 88      | 168       | 16    | 29        |
| Wisconsin      | 38      | 68        | 8     | 18        |

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## THE NEED FOR A NEW PARADIGM REGARDING THE PETROGENESIS OF THE DULUTH COMPLEX

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Recent high-resolution U-Pb isotopic age dates of zircons from Duluth Complex intrusions (Paces and Miller, in prep.) indicate that troctolitic and anorthositic series rocks have indistinguishable crystallization ages of about 1099 ( $\pm 0.4-0.9$ ) Ma (Table 1). These unexpected results compel a significant shift in what has come to be accepted as the basic paradigm of the Duluth Complex — that it is predominantly composed of two major rock series which differ in parent magma types, emplacement styles, crystallization histories, and intrusive ages. With his work in the Duluth area, Taylor (1964) was the first to subdivide the Duluth Complex into two distinct rock units on the basis of rock type, intrusive relationships, stratigraphic occurrence, and internal structure. At Duluth, anorthositic gabbroic rocks occur as a multiple-intrusive, structurally complicated, laminated suite of plagioclase ( $\pm$ olivine) cumulates, which Taylor characterized as an igneous breccia. A 4-km-thick, well-differentiated, stratiform sequence of troctolitic to ferrogabbroic cumulates occurs below the cap of anorthositic rocks at Duluth and has been termed the layered series.

Detailed mapping elsewhere in the complex revealed many of the characteristic features of the two rock suites defined at Duluth. With the publication of the MGS Centennial Volume in 1972, which included summaries of this mapping, the terms anorthositic series and troctolitic series acquired a semi-formal status as a chronolithologic classification. The genetic implications of this classification were first incorporated into a petrologic model by Weiblen and Morey (1980) who postulated that the older anorthositic series was produced from quartz tholeiitic basalt, a composition common among early rift lavas, by flotation of plagioclase and sinking of mafic minerals in Duluth Complex chambers. They further suggested that the rocks of the troctolitic series formed from olivine tholeiite parent magma, a common composition among younger rift lavas, which had been emplaced and fractionally crystallized in chambers between the anorthositic series cap and its ultramafic base. Most recently, Miller and Weiblen (1990) showed that both series could have been produced from a common primary magma of high-Al olivine tholeiite composition and suggested that the major difference between their parent magmas was the amount of intratelluric plagioclase crystals which they contained upon emplacement into the Duluth Complex. They concluded that structurally complex anorthositic rocks were formed from gabbroic magmas charged with as much as 60% plagioclase creating viscous crystal mushes, whereas the well-differentiated troctolitic series rocks fractionally crystallized from crystal-poor magmas. Miller and Weiblen hypothesized that crystal mushes were produced early in the evolution of the Midcontinent rift when magmas tended to pond in lower crustal chambers where high pressure would have promoted plagioclase flotation. As rifting progressed, crustal magma chambers were thought to have migrated to shallower depths and become more open to recharge and expulsion, thereby producing less evolved and less crystalline magmas. The ideas common to both these models, that anorthositic series rocks were significantly older than troctolitic series rocks and that each series was related to a particular stage in the tectonomagmatic evolution of the rift, were not based on definitive evidence. Rather, they were constructs that explained the observable differences in the internal structure, modal mineralogy, cumulus texture, mode of crystallization, and areal distribution of the two series. It now appears from the age dates that the anorthositic and troctolitic rocks evolved within a very short time interval in the 22-million-year (1108-1086 Ma) magmatic history of the Midcontinent rift.

Field evidence for the relative ages of the two series extends from that which clearly shows the anorthositic series to be the older to that which would best be classified as

ambiguous. In the definitive category are 1) inclusions of anorthositic rock in troctolitic/gabbroic rocks and the absence of the reverse, and 2) sharp intrusive contacts, rarely chilled, between troctolitic/gabbroic rocks and anorthositic rocks. Not definitive are contacts between troctolitic and anorthositic rocks described as obscure, ambiguous, or hybrid zones of mixing (Taylor, 1964; Phinney, 1972; Beltrame, 1974; Miller, 1986). Still other evidence, such as the presence of conformable anorthositic layers in stratiform troctolitic intrusions (Foose and Cooper, 1978; Bonnicksen, 1972; Phinney, 1969), the commonly leucocratic composition of many troctolitic rocks, and the successive emplacement of gradually less plagioclase-rich mushes in the creation of some anorthositic series suites (Miller, 1986), suggest that the transition from anorthositic (crystal mush) to troctolitic (magma-dominated) magmatism was gradational. Whereas these more ambiguous field relations tended to be overlooked or dismissed as minor complications to the general picture of two-stage magmatism, they are now seen as being consistent with the approximate contemporaneity implied by the age data.

Under the tighter time constraints imposed by the age dates, several new or modified models must be developed and tested to explain the petrogenesis of the anorthositic and troctolitic series. Some possibilities include :

- the two series represent a rapid progression from emplacement of plagioclase-enriched mushes to magma-dominated intrusions that could reflect the evolutionary stages of a lower crustal staging chamber from which progressively less crystal-rich magmas were tapped. Such an evolution may be caused by flushing of the staging chamber brought on by frequent recharge and expulsion.
- the two series represent the products of different magma processes, perhaps related to crystallization at different crustal depths prior to shallow emplacement into the Duluth Complex, which acted concurrently on a common primary magma type. Polybaric fractionation in multi-tiered staging chambers has been proposed to explain the compositional range observed in many Keweenawan hypabyssal and volcanic rocks (Klewin, 1989; Jerde, 1991).
- the two series were produced from a common parent magma moderately enriched in plagioclase crystals by flotation or flow concentration of the entrained plagioclase into the roof zone of the Duluth Complex, and subsequent fractional crystallization of the crystal-poor magma below the anorthositic cap. Such a model has been used to explain the gabbroic and overlying stratiform anorthositic rocks of the Keweenawan Mineral Lake intrusion of the Mellen Complex in Wisconsin (Olmsted, 1968) and the plagioclase-rich upper parts of the Logan Sills in northern Minnesota (Phinney, 1968).

Although the results of the age dates do not refute the possibility that the anorthositic rocks are slightly older than the troctolitic/gabbroic rocks, within the resolution of the dating (1.5 Ma), the very similar crystallization ages for the two suites strongly suggests a common petrogenesis over a large portion of the Duluth Complex. Therefore, the two-series classification may be a misleading representation of the intrusive history of the complex and should perhaps be abandoned. With more high-resolution dating of Duluth Complex intrusions, especially among the many discrete layered, troctolitic/ gabbroic intrusions now classified as being part of the troctolitic series, the two series chronolithologic classification may unravel still further. Other age dates (Table 1) from this study indicate that magma-dominated intrusions producing troctolitic/gabbroic rocks preceded and postdated the 1099 Ma event in other areas of the complex. Also, the multiple intrusive nature of both troctolitic/ gabbroic and anorthositic rocks and the variety of contact relationships observed between them imply extended and overlapping periods of both crystal mush and magma-dominated types of magmatism. While the validity of the series designations awaits geochronologic verification, an even more compelling reason to abandon the chronolithologic classification at this time is that it will free future petrologic and field studies of the bias imposed by its genetic implications.

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**Table 1.** Summary of U-Pb age dates of zircon and baddeleyite from Duluth Complex and related intrusive rocks (from Paces and Miller, in prep.).

| <u>Sample</u> | <u>Rock Unit</u>                                     | <u>Location</u> | <u><math>^{207}\text{Pb}/^{206}\text{Pb}</math> age</u> | <u>Analyses</u> |
|---------------|------------------------------------------------------|-----------------|---------------------------------------------------------|-----------------|
| FC1           | Anorthositic Series                                  | Forest Center   | 1099.0±0.3                                              | 5               |
| AS3           | Anorthositic Series                                  | Duluth area     | 1099.2±0.4                                              | 5               |
| PG2           | Troctolitic Series<br><i>Powerline Gabbro</i>        | Dunka R. area   | 1098.6±0.5                                              | 8               |
| D1            | Troctolitic Series<br><i>upper layered series</i>    | Duluth area     | 1099.3±0.3                                              | 6               |
| NLS5          | Nathan's Lay. Series<br><i>Basal contact unit df</i> | Gunflint Trail  | 1106.9±0.4                                              | 5               |
| SLI1          | Beaver Bay Complex<br><i>Sonju Lake Intrusion</i>    | Finland         | 1096.1±0.5                                              | 4               |
| SBG2          | Beaver Bay Complex<br><i>Silver Bay Intrusions</i>   | Silver Bay      | 1095.8±1.1                                              | 6               |

## RARE EARTH ELEMENT DISTRIBUTION PATTERNS IN EARLY PROTEROZOIC IRON-FORMATIONS OF THE PENOKEAN OROGEN, EAST-CENTRAL MINNESOTA

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The Penokean orogen in east-central Minnesota consists of two major components, an allochthonous fold-and-thrust belt on the southeast and one or more tectonic foredeeps on the northwest. The fold-and-thrust belt consists of several discrete structural panels or terranes bounded by discontinuities that have small-scale features consistent with large-scale northwest-verging nappes. Correlations between the panels are impossible. The fold-and-thrust belt flanks a tectonic foredeep which extended to the Mesabi range in northern Minnesota and the Gunflint range in Ontario.

Although structural details are complicated, the orogen also can be divided into an early extensional phase when sedimentary rocks, including iron-formation, were deposited on a southward-facing continental margin, and a subsequent compressional phase when these continental-margin deposits were folded and metamorphosed and when one or more northward-migrating foredeep basins were partly filled with iron-formation, as well as detritus derived from both the north and the south. The fact that iron-formation was deposited during both extensional and compressional phases of the Penokean orogeny is of considerable sedimentological significance.

Extensional tectonic conditions persisted in east-central Minnesota from approximately 2200 m.y. to about 1900 m.y.. Bodies of iron-formation deposited during that interval include those in Glen Township, the Cuyuna South range, the Trommald Formation of the Cuyuna North range, and the Philbrook area. The first two units have sedimentological features indicative of "Algoma-type" iron-formation, whereas the latter two units have mineralogical features indicative of hydrothermal-fumarolic processes.

Compressional tectonic conditions persisted from about 1900 m.y. to 1870 m.y. and iron-formations deposited during that time are assigned to the Animikie Group. They include the Biwabik and Gunflint Iron Formations of the Mesabi and Gunflint ranges, respectively, and the so-called unit A of the Ruth Lake area in the Emily district. These units of iron-formation have sedimentological attributes indicative of "Lake Superior-type" iron-formations.

We report here the results of 95 REE analyses. In general, Algoma-type iron-formations have moderate REE abundances ( $La = 0.1 \times 0.9 \times 1986$  North American shale composite--NASC), and are generally flat to somewhat depleted in the heavy elements (most  $La/Yb_n = 1 - 3$ ). In addition, iron-formation from Glen Township has consistently larger negative Ce anomalies (most  $Ce/Ce^*_n = 0.65 - 0.90$ ), whereas iron-formation from the Cuyuna South Range has small negative to positive Ce anomalies ( $Ce/Ce^*_n = 0.82 - 1.04$ ). Both units have positive Eu anomalies (most  $Eu/Eu^*_n = 1.1 - 1.5$ ). The Trommald and Philbrook iron-formations have REE concentrations that are similar to the Algoma-type iron-formations ( $La = 0.1 \times 1 \times 1986$  NASC). Rocks associated with the Philbrook iron-formations have generally flat REE patterns (most  $La/Yb_n = 0.7 - 1.9$ ) and consistent negative Ce anomalies ( $Ce/Ce^*_n = 0.73 - 0.93$ ). In contrast those from the Trommald Formation have HREE-depleted patterns (most  $La/Yb_n = 1 - 3$ ) and both positive and negative Ce anomalies ( $Ce/Ce^*_n = 0.58 - 1.24$ ), relative to the 1986 NASC standard. Iron-formations of the Animikie Group display a wide range of REE abundances. In the Biwabik Iron Formation, slaty units contain larger concentrations ( $La = 0.1 - 0.5 \times 1986$  NASC) than the cherty units ( $La_n = 0.09 - 0.1 \times 1986$  NASC American shale standard). The slaty units are slightly HREE-depleted (most  $La/Yb_n = 1.06 - 1.71$ ), whereas the cherty units have flat to slightly HREE-enriched slopes ( $La/Yb_n = 0.75 - 1.18$ ). In general both show very small, both positive and negative Ce anomalies ( $Ce/Ce^*_n = 0.8 - 1.6$ ) and positive Eu anomalies (most  $Eu/Eu^*_n = 1.2 - 2.0$ ). The Emily Formation, on the other hand, shows pronounced negative Ce anomalies ( $Ce/Ce^*_n = 0.32 - 0.87$ )

and higher total REE (most La =  $0.4 \times - 2.0 \times$  1986 NASC, but have similar slopes and positive Eu anomalies to the other foredeep iron-formations.

Although small local differences exist, broad similarities in the REE data imply that tectonic setting was not particularly important in iron-formation sedimentation. Rather the data imply that the various units of iron-formation were deposited from a compositionally homogeneous reservoir that persisted over at least 150 m.y. of geologic time. However the general lack of pronounced Ce anomalies and the presence of positive Eu anomalies implies that the reservoir was not simple "ocean water", but rather had a "hydrothermal" component.

The project was supported in part by the U.S. Bureau of Mines Selective Mining in Minnesota Minnesota Minerals Initiative and the Minnesota Department of Natural Resources, Division of Minerals, Public Geologic Sample Program.

# EVIDENCE OF AN EXHALATIVE CONTRIBUTION TO THE MANGANESE MINERALOGY OF THE TROMMALD FORMATION, CUYUNA IRON RANGE, EAST-CENTRAL MINNESOTA

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The Trommald Formation on the Cuyuna North range in east-central Minnesota was a major producer of iron ore for 80 years. Between discovery in 1904 and closing in 1984, the range shipped more than 106 million tons, much of which was ferromanganese ore that contained 5-15 percent manganese. It is that manganese component that sets the Cuyuna range apart from other Early Proterozoic iron-mining districts in the lake Superior region.

Until very recently, most geologic interpretations assumed that the ferromanganese ores were formed through the oxidation and leaching of a "green carbonate slate" protolith located at or near a transition between thick-bedded (cherty, granular) and thin-bedded (slaty, non-granular) iron-formation. These two lithofacies were thought to represent considerably different sedimentological regimes, the thin-bedded rocks deposited in "deeper" water below wave base under mildly reducing conditions the thicker bedded rocks deposited near or above wavebase under oxidizing conditions. In that model, the distribution of the ferromanganese ores would have been controlled by the pretectonic paleogeographic configuration of the Trommald depositional basin.

In an effort to better understand the paragenesis of the ferromanganese ores, we reexamined core from a hole drilled on the property of the Merritt Number 2 mine in the northwestern part of the North range. The site was one of four drilled in 1942 and the core has been in storage since the 1950s. The Merritt core is of particular interest because it intersects the entire Trommald Formation in the vicinity of unaltered "green carbonate slate."

We focus here on observations from the thick-bedded upper part of the iron-formation. Spherical structures are an important component of the cherty rocks. They were thought by Grout (1946) to be oolites or pisolites consisting of jasper and chert rims concentrically surrounding cores of quartz, feldspar, or acmite. In reality these spheroids are far more complex than envisioned by Grout. The typical spheroid contains a clast at its center, surrounded by bands of lateral mineral growth. Both the central cores and the associated rim material consist of a variety of minerals including acmite, rhodonite, rhodochrosite, Ba-feldspar, and/or hematite. Very little free quartz has been found; material previously thought to be jasper consists mostly of rhodonite or acmite.

Some spheroids have fairly simple mineralogical and textural attributes, but others are very complex. Some of the observed complexities include: clasts of Ba-feldspar surrounded by rhodochrosite; rhodonite surrounded successively by hematite, Ba-feldspar and ultimately rhodochrosite; clasts of rhodonite surrounded by rhodochrosite; clasts of acmite surrounded by red cherty-looking acmite; clasts of rhodonite surrounded by red cherty-looking rhodonite; clasts of Mn-oxide surrounded by acmite; clasts of rhodochrosite surrounded by acmite; clasts of rhodochrosite surrounded by hematite, which in turn is surrounded by rhodochrosite.

Most of the minerals described above, other than acmite which was first described by Grout (1946), have not been reported previously from the Trommald Formation. Of particular interest is the Ba-feldspar which also occurs in veins with rhodonite and carbonate, and as a secondary mineral surrounding grains of stoichiometrically pure K-feldspar. The composition of the Ba-feldspar in these rocks varies from about 10 to 22 mole percent  $\text{BaAl}_2\text{Si}_2\text{O}_8$ .

Ba-feldspar has been reported from only a few localities in the world. Much of it is associated with deposits inferred to be of exhalative origin, including manganese deposits and/or Pb-Zn deposits. These include Broken Hill, New South Wales (Segnit, 1946), southern Grampian Highlands, Scotland (Coats and others, 1984; Fortey and Beddoe-Stephens, 1982), central North

Greenland (Jakobsen, 1990), Sweden (Bostrom and others, 1979; Lundstrom and Wadsten, 1979), Japan (Nakano, 1979), Wales (Smith and others, 1949), Namibia (Vermaas, 1953), and Greece (Reinecke, 1982). Stratiform tourmalinites and barite veins also exist on the North range, and are additional evidence for a fumarolic hydrothermal component for the origin of these deposits.

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HIGH TEMPERATURE HYDROTHERMAL ALTERATION  
ASSOCIATED WITH PGE ENRICHMENT OF Cu-Ni SULFIDES, DUNKA ROAD,  
DULUTH COMPLEX, NE MINNESOTA

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The Dunka Road Cu-Ni deposit occurs at the base of the Partridge River Intrusion (PRT) within the 1.1 Ga Duluth Complex. The deposit is approximately 5 km by 1.25 km in areal extent. Relogging of 80 drill holes has identified seven major lithologic units that can be correlated over the whole deposit as well as 27 km along strike within the PRT (Geerts, 1991; Severson and Hauck, 1990). All units (I through VII) are primarily composed of troctolitic anorthosite to pyroxene troctolite and in lesser amounts, gabbroic anorthosite and olivine gabbro. Units II, VI and VII have basal ultramafic units; other contacts between units have been interpreted on the basis of other mineralogical and textural differences (Figure 1).

About 90% of the total sulfide mineralization occurs within Unit I. It is interstitial and widespread, however it varies in mode from rare up to 5% and it also varies in continuity and thickness from 10 cm to 10 m. Major sulfide minerals include pyrrhotite, chalcopyrite, pentlandite and minor cubanite. These are usually primary. Minor amounts of bornite, native copper, sphalerite, galena, pyrite, talnakhite and mackinawite or valleriite occur throughout unit I and textures indicate that in most cases these minerals tend to replace the primary mineral assemblage.

Three Cu/PGE enriched horizons have been identified within unit I (Geerts, 1991), the most continuous of which has been called the RED horizon. This horizon occurs directly beneath ultramafic layer (IIa, Figure 1) in the uppermost portion of unit I. It ranges from 3 to 10 m thick and contains an average Cu content of 0.57% and Pt + Pd contents of 986 ppb (Geerts, 1991). It has been recognized in 87% of the holes logged. Texturally this zone is more coarse-grained than the rest of unit I and contains more secondary sulfides than elsewhere in the section. For example bornite, pyrite, sphalerite, galena and native copper have only been recognized in the enriched zones, in particular the RED zone.

Detailed logging, both below and above the RED horizon shows that the predominant host rock, anorthositic troctolite, exhibits subtle fracturing and alteration. Plagioclase has been saussuritized, pyroxene is now greenish uralite and olivine is serpentinized. Olivine in Unit II(a) above the RED is also serpentinized. The majority of the sulfide itself is coarse-grained (5 mm) and commonly rimmed by secondary red-brown biotite. Plagioclase both inside and outside of this zone is cumulus, occurring as anhedral to subhedral, tabular to lath-shaped crystals. The average grain size varies from 2 to 6 mm throughout all the troctolitic rocks (Units I-VII), however within the red zone the grain size increases to 4-10 mm.

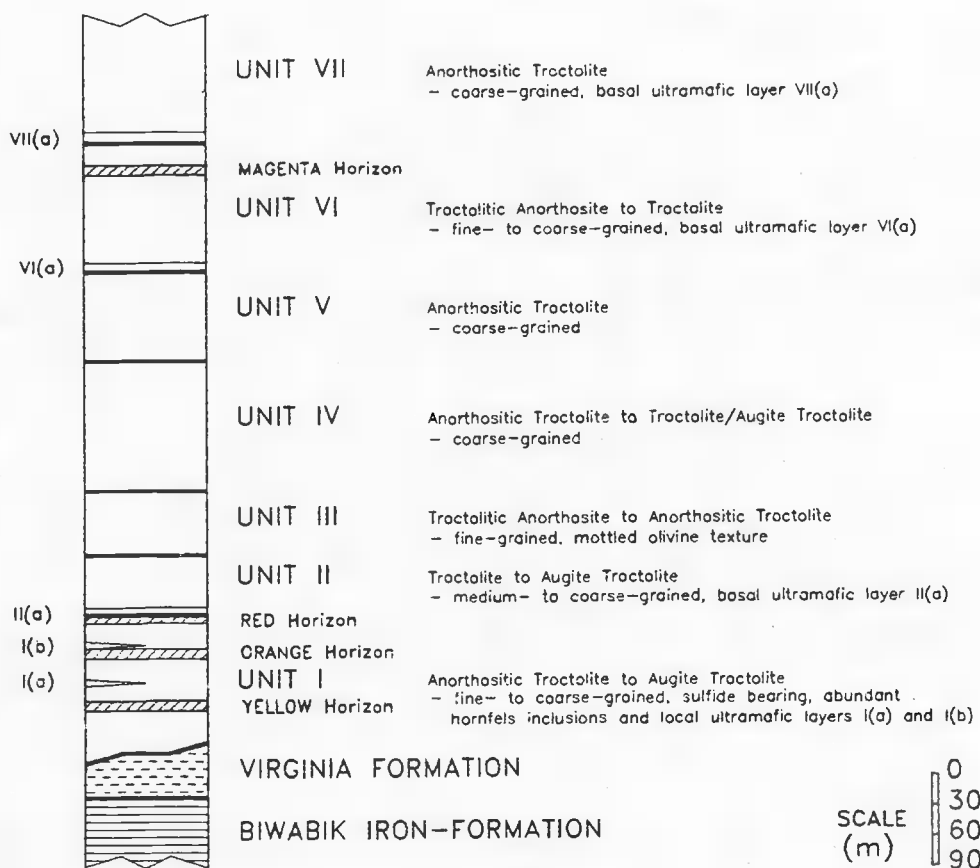
Plagioclase in 50% of the samples throughout the section contains reddish-black needle-like inclusions. Within the RED zone, where plagioclase is in contact with fine-grained secondary sulfides (in particular bornite and remobilized chalcopyrite), the needles are absent from the edges of the plagioclase. Where the needles are absent in a particular plagioclase crystal, the plagioclase shows undulatory extinction. These plagioclase

crystals are interpreted to have been recrystallized during sulfide "remobilization". Microprobe analysis of plagioclase from 18 samples from within and outside the zone show that generally An content varies from 60-65% whereas within the recrystallized areas the An content has been increased to 75-90%. These compositions of plagioclase are consistent with alteration by saline solutions at temperatures in excess of 700°C (Sassani and Shock, 1990).

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FIGURE 1. GENERALIZED IGNEOUS STRATIGRAPHIC COLUMN



## THE KENORA - KABETOOGAMA DIKE SWARM: RESULTS OF TRACE ELEMENT STUDIES

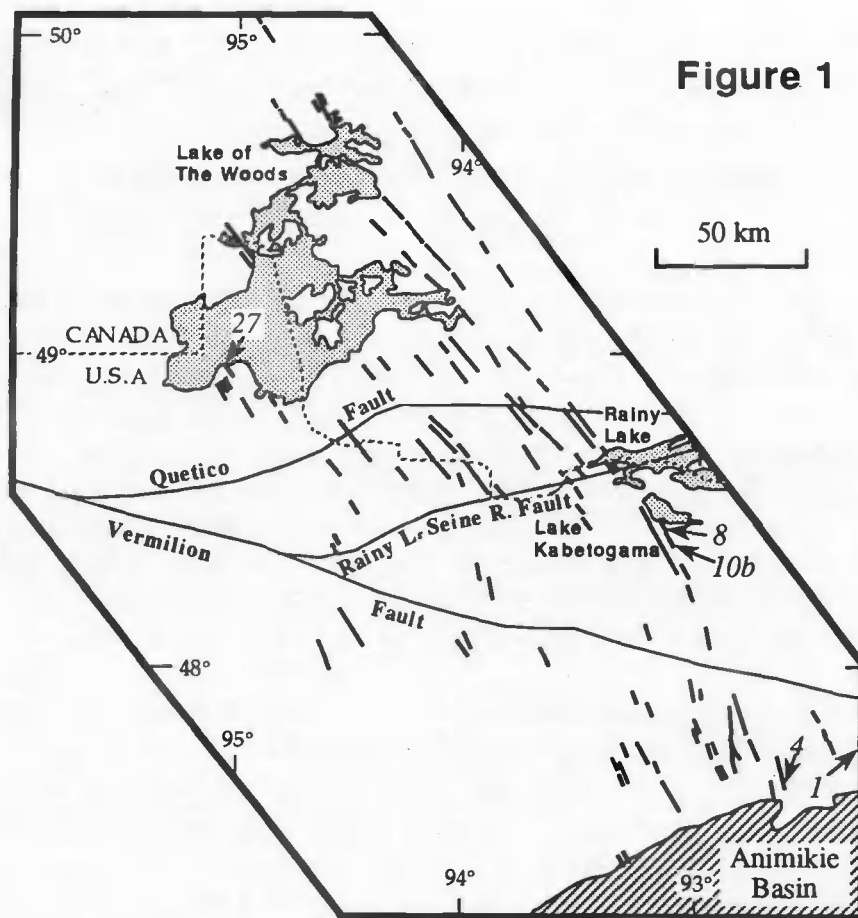
Andrew D. Moshoian, Karl R. Wirth and John P. Craddock  
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The Kenora - Kabetogama mafic dikes comprise a swarm that extends from the Mesabi Iron Range, Minnesota, northwest to Kenora, Ontario, a distance of about 300 km (Figure 1). A Rb - Sr isochron for the dikes gives an age of  $2120 \pm 67$  Ma (Beck and Murthy, 1982), suggesting that dike emplacement may have occurred contemporaneously with Early Proterozoic extension in the Animikie Basin of the Lake Superior region (e.g., Morey, 1983). The KK dikes strike ~N-S in northeast Minnesota and ~E-W in west-central Minnesota and everywhere have vertical dips and cross-cut a variety of Archean granite-greenstone terranes. The dikes are undeformed and are everywhere parallel to fault-fracture arrays in the country rock that are filled with epidote, quartz and calcite (Craddock and Moshoian, 1991). Strike-slip offsets are common along most of these brittle features which are closely spaced (~1 meter), regionally distributed and appear genetically related to the evolution of the KK mafic dikes (Penokean?).

Trace element concentrations were determined for 12 samples. The concentrations indicate significant geochemical variation between dikes. Southwick and Day (1983) recognized that many of the dikes have been deuterically altered to secondary hydrous mineral phases. Most of the incompatible elements, with the exception of some of the alkali elements, are well - correlated suggesting that the trace elements remained relatively immobile during this alteration episode. The dikes can be separated into three distinct types on the basis of their Rare Earth Element (REE) patterns (Figure 2). Group 1 dikes have high total-REE concentrations relative to C1 Chondrite (Sun and McDonough, 1989) (samples 10a, 10b, 13). Sample 10b, which is located near Lake Kabetogama, is characterized by high  $(La/Sm)_{CN} = 1.67$  and  $Yb_{CN} = 50$ . Rocks from this group also have a significant negative Eu-anomalies, suggesting that plagioclase fractionation has occurred. Group 2 dikes, represented by sample 1, are LREE enriched with  $(La/Sm)_{CN} = 2.37$ , but with low  $Yb_{CN} = 10.76$ . The slope of the REE pattern of this sample is the steepest of all the samples analyzed, and crosses the patterns of other dike rocks. Sample 1, which is located just west of Tower, MN, also shows a positive Eu-anomaly. Group 3 dikes (samples 4, 8, 9, 15, 17, 19, 26, 27) show nearly flat REE patterns, with  $(La/Sm)_{CN}$  ranging from 0.97 (sample 04) to 1.08 (sample 8), and  $Yb_{CN}$  ranging from 12 (sample 4) to 31 (sample 8). These rocks were taken from various locations around northern Minnesota (Figure 1).

Figure 3 is a spider-diagram of trace element concentrations normalized to N -MORB with increasing incompatibility from right to left. All of the rocks of the representative suite show progressive enrichment in the highly incompatible elements. Most samples have normalized Ta/La ratios > 1 except for those in Group 1 (eg. sample 10b). Normalized Sr values are variable as well, and are likely due to plagioclase fractionation. Group 3 dikes are enriched in Ba relative to those of Group 1 which have higher La/Sm ratios (Figure 4). On many tectonic discriminant diagrams (Figure 5), most dikes plot on the fields of MORB (Group 3) or volcanic arcs (Group 1 and 3). Sample 1 (Group 2) is highly enriched in Ta and plots in the field of within-plate magmas.

The trace element data indicate that the dike samples can not be related by simple crystal fractionation. We interpret the data to indicate that the dike magmas were derived from different mantle sources, or that they were variably contaminated with continental crust or lithosphere, or , or both.

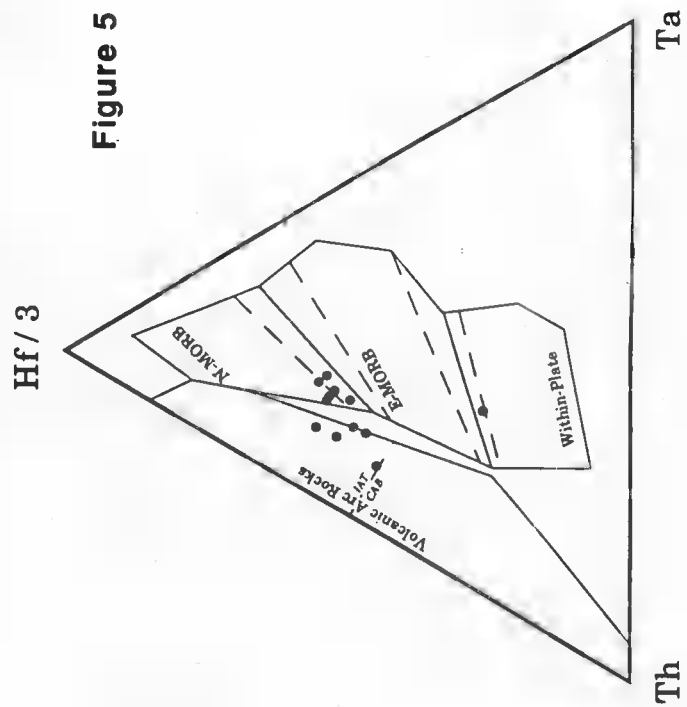
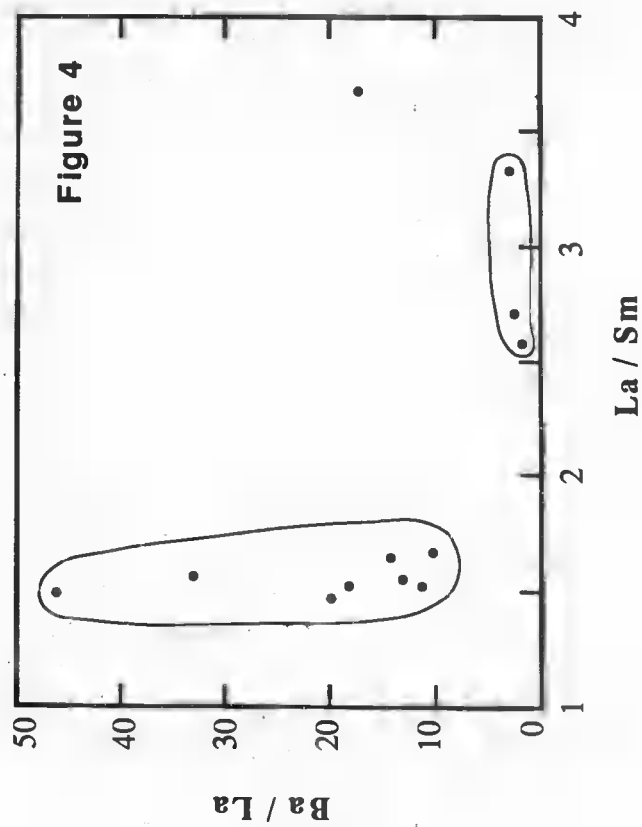
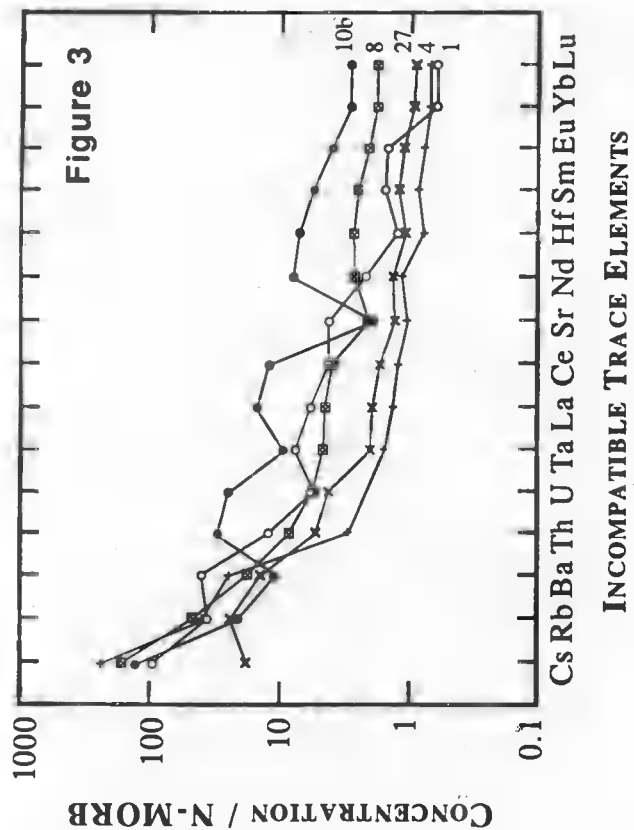
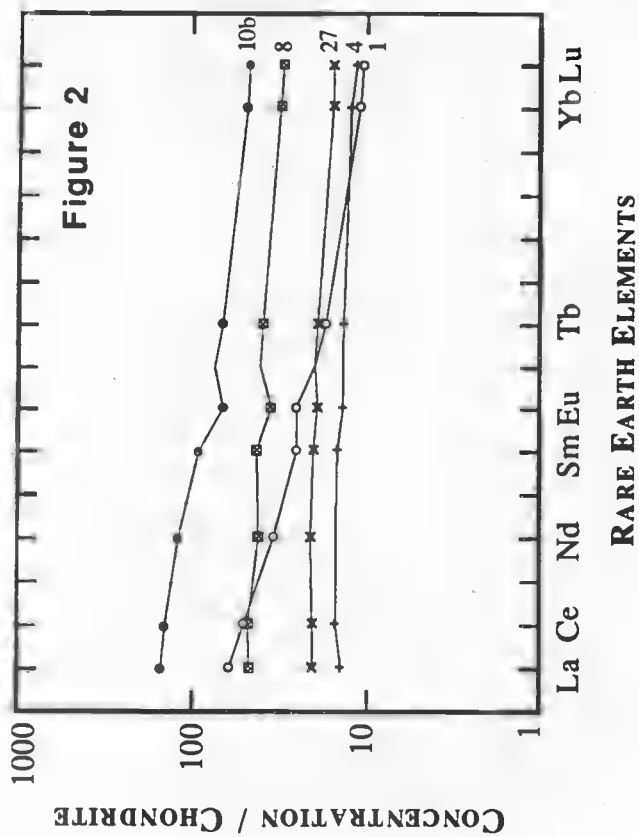


#### Figure Captions

- Figure 1 Map of Kenora - Kabetogama dikes in Northern Minnesota and Southern Canada. Locations of selected dikes are shown in italics. Modified from Southwick and Day, 1983.
- Figure 2 REE patterns of selected dike samples.
- Figure 3 Incompatible trace element patterns of selected dike samples.
- Figure 4 Ba/La vs. La/Sm diagram of all samples analyzed
- Figure 5 Hf/3 - Th - Ta diagram of all samples analyzed. (From Wood et al., 1979)

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# PENOKEAN STRUCTURAL TRENDS DEFINED FROM FORMATIONAL CONTACTS AND CLEAVAGE ANALYSIS ALONG THE GOGEBIC RANGE, WISCONSIN

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## ABSTRACT

Structural reconstruction of the Paleoproterozoic Tyler Formation by rotating out the dip of Mesoproterozoic Keweenawan bedding orientation along the Gogebic Range in northern Wisconsin suggests that Paleoproterozoic units (Tyler and earlier formations) were gently deformed along axes trending  $04^{\circ}$  toward S.  $79^{\circ}$  W. prior to deposition of Mesoproterozoic quartzite (basal Keweenawan Bessemer Quartzite). This analysis suggests that the cleavage near Hurley, Wisconsin, is not a slaty cleavage, but is probably fracture cleavage related to late Keweenawan tectonism.

The lower Keweenawan (Mesoproterozoic) Bessemer Quartzite rests with slight angular discordance on the Penokean Tyler Formation (Paleoproterozoic). All the units generally dip at  $70^{\circ}$  to the northwest (Montgomery, 1977). We have rotated the bedding of Tyler units immediate below the Bessemer contact back to the pre-Bessemer position using the bedding orientation of the Bessemer for rotation. At the western end of the Gogebic, the Tyler dips approximately  $15^{\circ}$  to the northwest. In the east, the Tyler dips approximately  $15^{\circ}$  to the southeast. Analysis of these localities on steronets and computer structural rotation programs suggests a fold axis trending east-north-east and plunging gently to the west-south-west. Rotation of the cleavage in the Tyler to its presumed pre-Bessemer orientation results in a pre-Bessemer dip to the south, which we find incompatible with our understanding of Penokean deformation along the Gogebic Range.

On the basis of reconstructed thickness of post-Tyler strata along the Wisconsin-Michigan state line, the recognition of well developed slickensides along the cleavage planes, and minor, centimeter-scale offset of Freda and Tyler units across those cleavage planes, we suggest that the cleavage is a fracture cleavage related to late Keweenawan tectonism, that Tyler and Keweenawan sedimentary sections are probably repeated, and that measured thicknesses are too great. Hotchkiss (1919) clearly recognized bedding plane faults near the base of the Ironwood Iron-formation on detailed maps of underground workings along the Gogebic Range. The faults are recognized by offsets in diabase dikes that cut the sedimentary strata at a high angle.

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# GEOLOGIC SETTING OF THE EARLY PROTEROZOIC METAL-RICH VOLCANICS OF THE UPPER GREAT LAKES REGION

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## ABSTRACT

Since the late 1960s, more than 100 million short tons of volcanogenic massive-sulfide mineralization have been measured and inferred in northern Wisconsin. Significant precious metal values are associated with many of the known deposits.

The deposits occur within the Early Proterozoic Penokean fold belt (1,850 - 1,900 Ma), which has been divided into two major terranes: the northern terrane, which consists of a supra-crustal sequence deposited on the Archean basement, and a southern terrane, which is composed of volcanogenic rock and Early Proterozoic granite. This southern terrane, the Wisconsin Magmatic Terrane (also called the Wisconsin Penokean volcanic belt), is characterized by island-arc assemblages containing abundant calc-alkaline metavolcanic units and associated lesser amounts of metasedimentary rock. Within this geologic framework, three distinct environments appear to host massive sulfide mineralization: syngenetic stratabound and stratiform sulfide mineralization within, along the flanks of, or near the stratigraphic top of the felsic centers; syngenetic stratabound and stratiform massive-sulfide mineralization associated with cherty magnetic iron-formation in the main volcanic arc sequence; and epigenetic stringer sulfide mineralization and syngenetic stratabound and stratiform massive sulfide mineralization associated with mafic piles within the back-arc basin sequence. The three defined host environments and their associated meta-argillite formations appear to be major regional features controlling the localization of metal-bearing massive sulfide mineralization in the west part of the area. Other host environments will undoubtedly be identified as exploration continues in the area.

EARLY PROTEROZOIC LEPTITE & HALLEFLINTA (TUFF & TUFFITE)  
SEQUENCES OF SOUTHERN FINLAND REINTERPRETED AS SHEAR ZONES:  
SIGNIFICANCE TO LAKE SUPERIOR GEOLOGY

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Many Early Proterozoic volcanogenic sequences in southern Finland and adjacent Sweden have long been interpreted as bedded tuffs and "tuffites" (i.e., epiclastic volcanic sediments), and commonly have been called leptites and halleflintas. While definitions of these unfamiliar terms vary, even in Fennoscandia, leptites and halleflintas can be described as fine-grained quartzofeldspathic metavolcanic rocks. The halleflintas are the finer grained of the two ( $<0.25\text{mm}$ ) and are commonly thinly bedded ( $<2.0\text{ cm}$ ). A restudy of several such units in Finland has provided evidence for a structural origin as tectonic layering (i.e., shear bands) rather than as primary bedding.

We studied a 1 km wide vertical shear zone in the Tampere Schist Belt in some detail. Massive plagioclase porphyry was clearly the main protolith; in a zone about ten meters wide there is a gradual transition from unsheared plagioclase porphyry to highly sheared and thinly banded rock. Glassy pseudotachylite, evidently the product of intense granulation and fusion due to frictional heat, was found at two spots. Kinematic indicators suggest a dominant horizontal movement in this zone. Color differences between adjacent thin bands appear to reflect compositional changes and may be largely due to metasomatism by sodium-, potassium-, magnesium-, silica-, and calcium-bearing solutions rather than to original compositions of thin beds. Silicification appears to have been a widespread process. Subsequent amphibolite and greenschist grade metamorphism has produced skarns and other metamorphic rock types in the thinly banded sequence.

The above shear zone contains sulfide mineralization, and intensive drilling has attempted to locate sphalerite mineralization that was originally spotted in large mineralized glacial erratics. Drilling has resulted in intercepts of Zn-Pb-Ag mineralization. Elsewhere in the Tampere Schist Belt, gold has been discovered in shear zones; in one silicified shear zone, 10 ppm Au is present.

In another wide shear zone in the Southern Finland (Orijärvi) Leptite Belt, three sulfide bodies have been mined out. Metsämonttu was a Zn-Pb deposit, Aijala was a Cu-Zn deposit, and Orijärvi was a Zn-Cu deposit. The significance of shearing in the vicinity of the mines has been overlooked, and while the ore bodies were logically interpreted as strata-bound Kuroko-type volcanogenic sulfides, we emphasize the possibilities of an epigenetic-metasomatic origin or a remobilization of primary volcanogenic sulfide in this zone of structurally-prepared volcanogenic rock.

We also visited leptite belts in the Stockholm area, and made observations similar to those cited above. At one locality, sheared rocks are in close proximity to a mine that has been in existence for centuries. Photographs in the literature on parts of leptite belts that we were not yet able to visit are highly suggestive of tectonic layering.

Could some "tuff sequences" of the Lake Superior region also be shear zones? We are positive that some "thinly bedded sequences of mafic and felsic tuffs" in Archean terranes that we have even mapped ourselves in decades past are, in reality, the result of shearing. A reinspection of such "tuff sequences" may be warranted, for it could make additional terrane worth prospecting for both gold and sulfide deposits.

**PETROLOGY AND ORIGIN OF THE NORTHERN COLVIN CREEK BODY,  
DULUTH COMPLEX, NE MINNESOTA  
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NATURAL RESOURCES RESEARCH INSTITUTE, DULUTH**

The Colvin Creek Body (CCB, Colvin Creek Hornfels of Bonnichsen 1972, Tyson 1975) occurs within coarse-grained troctolite, anorthositic troctolite, and augite troctolite of the Partridge River Intrusion (PRI) of the 1100 m.y. Duluth Complex, NE Minnesota. It is located about 90 km N of Duluth and about 13 km ENE of Hoyt Lakes. This is about 5 km SE from exposures of the basal contact of the Duluth Complex, the CCB is estimated to be about 600-1200 meters above the base of the Complex.

This hornfels body consists of a series of fine-grained to medium-grained units of basaltic composition and a coarser-grained gabbroic unit. In the finer-grained rocks textures are granoblastic and fabrics include both lava flow and sedimentary features. In the past the CCB has been interpreted as a large xenolith of Keweenaw basalt. More recently it has been suggested that it is of igneous origin (Severson and Hauck 1990).

Field relations within the CCB are consistent with the hypothesis that the hornfels block is a stratigraphic stack of sediments and basalts, contact metamorphosed to pyroxene-hornfels facies by the Duluth Complex. This block has been rotated 70-90 degrees so that a cross-section is now exposed at the surface. Dips are now to the north and most indicators give a northward topping direction. Aside from the rotation there is little definite kinematic evidence of folding or faulting, although some bedding parallel faults may be present, along with some sigmoidal clots of pyroxenes and oxides. The block strikes approximately N60E along a length of 2400 meters with an apparent stratigraphic thickness of 680 meters. The hornfels block has an areal extent of about 1.6 sq. km. The CCB has not been drilled and there is no good estimate of how far it extends below the surface.

The actual boundaries of the CCB are defined from outcrop control and from the magnetic signature, the CCB is a magnetic high similar to the nearby Powerline Gabbro. This is probably due to both the magnetite contained in rocks and ubiquitous magnetite and augite-magnetite dikes, veins, and masses.

#### MAIN LITHOLOGIC UNITS

The five main units present at Colvin Creek are described below in order from north to south (youngest to oldest).

The GOG is a medium-grained to very coarse-grained, oxide rich, gabbro to olivine gabbro. It contains some areas of modal layering, and has anorthosite inclusions. Plagioclase percentage varies from 50 to 80% in the unit itself and up to 85-90% in the anorthosite inclusions. Olivine content ranges from 10-25%, augite 5-15%, and oxides 1-10%. This is clearly an igneous unit, similar to the Powerline Gabbro to the east, it is apparently unmetamorphosed, and assumed to be younger than the basaltic portion of the hornfels. The GOG makes up about 15% of the exposed CCB.

The "Cross-Bedded Belt" (XBB) rocks are granoblastic, fine to medium fine-grained, have a dominant mineralogy of plagioclase (An 65-70), aluminous pyroxene, magnetite, ilmenite, with traces to a few percent of olivine, orthopyroxene, cordierite, biotite, and covellite. There are millimeter to centimeter scale, high angle cross-bed sets, defined by modal layering with pyroxene and oxide bases. The bed-sets have a 25-40 centimeter thickness but are not traceable for any great distance. The granoblastic texture, fine grain size, cross-bedding, and the stratigraphic thickness of about 300 meters lead this to be interpreted as a metasedimentary unit. This unit makes up about 35% of the hornfels body. At 300 meters, the thickness of the XBB unit is about the same stratigraphic thickness as the total of Keweenaw interflow sedimentary rock

measured on the Lake Superior Shore.

Ameboidal Augite (AA), is a granoblastic, fine to medium-grained, generally massive unit. The mineralogy is essentially the same as the other granoblastic units, plagioclase, augite, magnetite, and ilmenite +/- olivine. There are concentrations of augite and Fe-Ti oxides occurring as small stringers more or less perpendicular to bedding and rounded clots of the same material defining the bedding or layering. These parallel layers of augite and Fe-Ti oxide concentrations are interpreted to be flow tops, indicating flows roughly one meter or less thick up to as much as ten meters. Flow tops are actually only seen for a few meters length in scattered locations. This unit has pyroxenite zones along its upper contact with the XBB unit and contains numerous veinlets (and healed joints) of pyroxene intimately mixed with Fe-Ti oxides. This is interpreted as a subaerial, amygduloidal, metavolcanic unit making up about 15% of the CCB.

Amygduloidal Gabbro (AMG), is stratigraphically below the AA and is very similar to the AA in its mineralogy and granoblastic texture. Here the pyroxene and oxide concentrations are less regular, and there are concentrations of plagioclase occurring as small clots throughout the unit. This is also thought to be a subaerial metavolcanic unit constituting another 15% of the total hornfels.

Massive Colvin Creek (MCC), at the base of the hornfels sequence, is a massive rock of roughly the same mineralogy and composition as the metavolcanic units, containing plagioclase, augite, Fe-Ti oxides, but it also has areas of high olivine concentration. These are ophitic zones but it is uncertain if these are an original igneous feature or due to metamorphism. The MCC contains some small cavities and has plagioclase clots similar to those in the AMG unit, but lacks well defined volcanic features. In a few locations there are large plagioclase phenocrysts, their origin is also unclear. The contact with the AMG unit above is gradational over about 1-10 meters. This is thought to most likely be a thick lava flow or near surface sill. This unit covers about 20% of the exposed area at Colvin Creek.

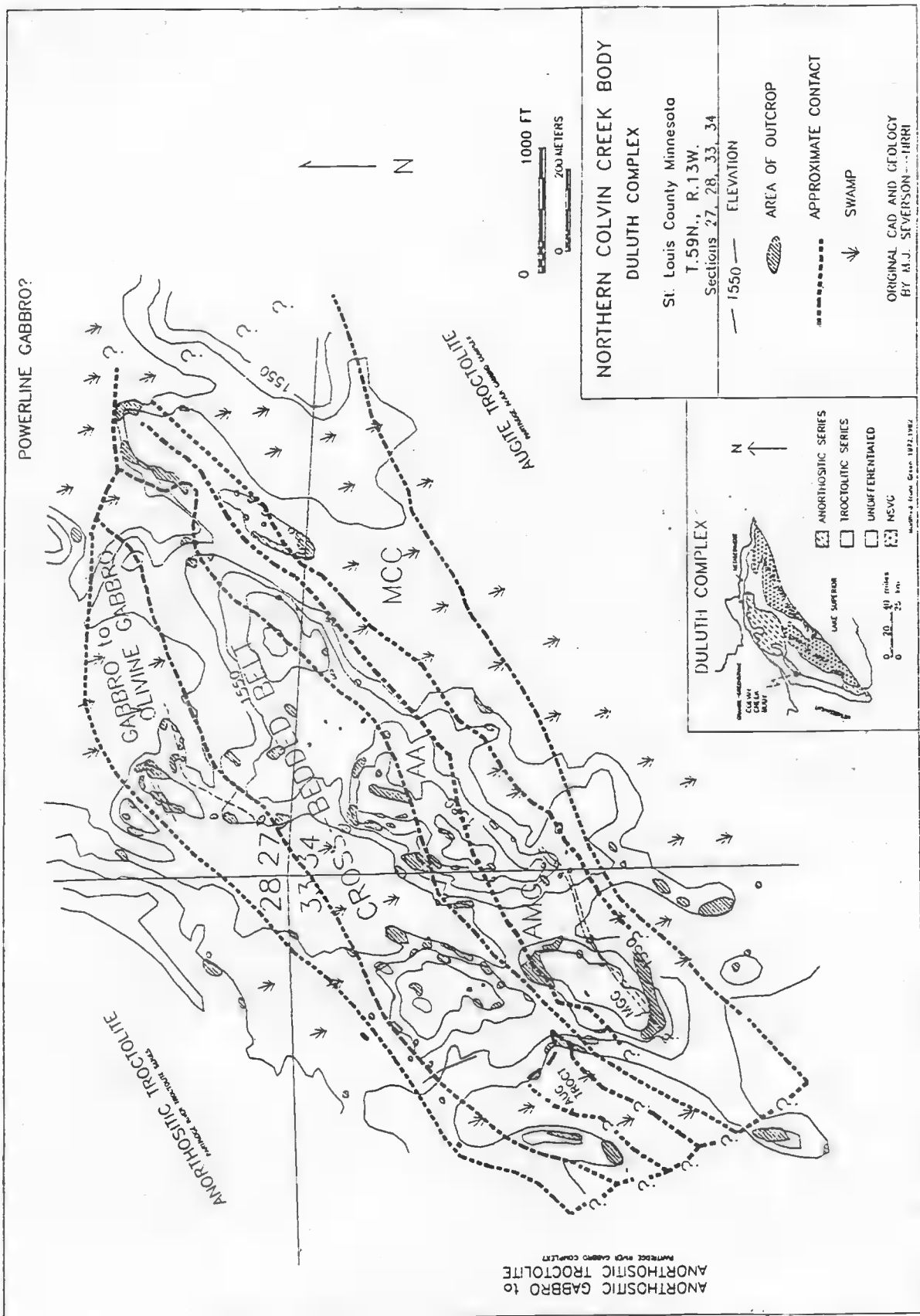
Whole rock geochemistry indicates that the CCB rocks are similar to Keweenawan igneous rocks and selected interflow sediments of the North Shore Volcanic Group, but are not strict analogues for any unit in the Keweenawan.

This work has been supported by the UMD Graduate School, UMD-NRRI, and the Coleraine Minerals Research Laboratory.

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VARIATIONS IN METAMORPHIC GRADE OF METAPELITES ALONG  
TRANSECTS ACROSS THE QUETICO SUBPROVINCE  
THUNDER BAY, ONTARIO

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The Archean rocks of the western Superior province of the Canadian Shield have been subdivided into a series of subprovinces. These subprovinces form east-west trending terranes typified by either metavolcanic successions and granitic intrusive rocks as represented by the Wawa and Wabigoon subprovinces, or by metasedimentary gneisses and migmatites characteristic of the Quetico and English River subprovinces.

Many workers have attempted to define the boundaries separating these subprovinces from one another. These attempts commonly focus on a comparison between adjacent subprovinces with regard to lithological character, orientation of structural elements, metamorphic grade, geophysical anomalies, and geochemical parameters. Although such comparisons are valuable in identifying differences between adjacent subprovinces, the actual boundary remains a poorly defined feature in most cases.

The objective of the present study was to analyze metamorphic index minerals in metapelites and to compare these results to typomorphic mineral assemblages. Much of the analytical work was confined to garnet because of its widespread occurrence in the metapelites.

One hundred thirty two garnets were analyzed using a Hitachi 570 S.E.M. Results show that the garnets cover a range of compositions from almandine (54-92) spessartine (1-33) pyrope (2-25) grossularite (0-17) suggesting a parent rock composition relatively low in calcium and rich in iron and magnesium.

With increasing grade of metamorphism garnet compositions reflect decreasing CaO and MnO and increasing FeO and MgO contents. Geobarometry using the equilibrium assemblage garnet + sillimanite + plagioclase + quartz resulted in pressures of  $5 \pm 1.5$  Kbar.

Electron microprobe analyses of twenty samples containing biotite and garnet showed temperature ranges from 517°C in metasedimentary rocks to a maximum of 714°C in the migmatite complex. In general, a pattern of steadily increasing temperatures northward is interrupted by a rather sharp drop north of the highest grade rocks.

The widely held view that the metasedimentary terranes of the western Superior province possess a symmetric distribution of metamorphic grades from low-grade rocks near the margins to higher grade rocks near the central parts is not supported by this detailed study of the Quetico subprovince north of Thunder Bay.

It is common to find high-grade rocks juxtaposed with low-grade schists near the subprovince margin. The variations in metamorphic grade are not only profound in transects across the regional strike of the rocks but also occur parallel to the strike. The latter variations are particularly well demonstrated near the

southern margin where high grade schists and gneisses and low-grade slates are exposed in outcrops over a strike distance of about 10 km.

The variations in metamorphic grade throughout the Quetico subprovince between high-grade and low-grade assemblages and corresponding mineral analyses, contradict a simplistic distribution.

An explanation for this pattern of distribution lies to some extent in the evolution of the Quetico terrane. Several models invoking the mobilist viewpoint have been presented in the literature. Based on the evidence from this study, we conclude that a model of subduction-driven accretion of Archean crustal elements best explain the field and laboratory data.

The Quetico terrane represents an accretionary prism composed primarily of detritus shed southward from the Wabigoon island arc and microcontinent terranes. The prism comprises quartzofeldspathic and pelitic sediments. Southward oblique accretion of the Wawa terrane signalled the onset of polyphase deformation, low pressure regional metamorphism, and development of thrusts. Northward dipping thrusts and thrust nappes resulted in tectonic stacking of diverse rock types from different levels of the accretionary wedge. Continued north-south compression led to the coaxial refolding of earlier folds and thrust sheets, and the development of a pervasive sub-vertical, east-west striking schistosity. Late north-south dextral transpression is seen in structures reflecting more brittle deformation and the intrusion of post-kinematic plutons near the southern margin. This late intrusive activity produced contact metamorphic effects which overprint the regional metamorphism.

At the present level of erosion, the pattern of distribution of metamorphic grade and the orientation of planar and linear structures appears to correspond to the proposed evolutionary model.

The boundaries between the Quetico subprovince and adjacent volcanic terranes in the area covered by this study are best described as products of a complex fault-fold geometry. In the area studied there appears to be no distinct line of demarcation between subprovinces.

## **SULFIDE AND PGE MINERALIZATION AT THE BASAL CONTACT OF THE MINNAMAX DEPOSIT, DULUTH COMPLEX, NE MINNESOTA**

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The Minnamax (Babbitt) Cu-Ni deposit, located within the Partridge River Troctolite of the Duluth Complex (1.1 Ga), northeastern Minnesota (Fig 1), contains both troctolite-hosted disseminated ore and footwall-hosted massive sulfide ore. This talk pertains to the massive sulfide ore zone, which is restricted to a small portion of the deposit, and is referred to as the Local Boy area. Detailed relogging of 76 underground drill holes, along with pertinent surface holes, has been completed within the Local Boy area (from drifts B, C, and D).

Relogging of drill core indicates a highly undulatory nature of the basal contact of the Duluth Complex with the footwall Virginia Formation. Intrusive rocks of the Complex consist of augite troctolite, troctolite, and norite; all exhibit gradational contacts with each other and all may occur at any stratigraphic position relative to the undulatory basal contact. However, norite is the most common rock type adjacent to sedimentary hornfels inclusions and at the basal contact due to contamination of the magma. The spatial configuration of the intrusive rocks indicates that the troctolite, etc. was intruded as multiple pulses along bedding planes of the Virginia Formation.

The Virginia Formation hosts the majority of the massive sulfide ores which are present within hornfels inclusions positioned above the basal contact, and within the footwall rocks at and below the basal contact. Massive sulfide ore is not as common within the intrusive rocks, and when present it is generally in close proximity to hornfels inclusions. Megascopic ore textures are extremely varied, but all textures are indicative of structural preparation in the footwall rocks. Overall, the massive sulfide ores are spatially distributed in a spotty manner in an east-west (EW) direction that corresponds to a major EW-trending anticline present within the footwall rocks. All these factors suggest that an immiscible sulfide melt was injected into the structurally prepared footwall rocks along the anticlinal axis in a "vein-like" setting. At some later period, the footwall-hosted massive sulfide ore zone was re-intruded by multiple sills of the troctolitic rocks. The end result is a disjointed zone of mineralized inclusions and mineralized footwall rocks separated by "barren" intrusive rocks.

Sulfide textures indicate that the sulfides formed by cooling of a monosulfide solid solution (MSS) followed by limited replacement at very low temperatures. Minerals contained within the sulfide ore are dominantly pyrrhotite, chalcopyrite, cubanite, and pentlandite. Locally present are maucherite, sphalerite, bornite, talnakhite, mackinawite, and an unknown Cu-sulfide ("Cp"). Also present in minor amounts are native silver (both primary and secondary), parkerite, chalcocite, covellite, godlevskite, violarite, magnetite, and zincian hercynite.

Although no discrete PGE minerals were identified, analytical results (from 1,050 drill core samples with an average sample interval of 5 to 10 feet long) of the high-grade (> 1% Cu) massive sulfide ore confirms the presence of several anomalous PGE values. These spot values are mainly confined to an EW-trending zone that also roughly corresponds to the EW-trending anticline (Fig 2). Maximum values obtained in the Local Boy massive sulfide ores include: Pd = 11,100 ppb; Pt = 8,300 ppb; Au = 10,900 ppb; and Ag = 34 ppm. Underground drill hole 10198 probably represents the best precious metal-bearing drill hole found to date within the

Complex. Within the 300 foot long hole are ten Pd values  $> 1$  ppm, five Au values  $> 1$  ppm, and three Pt values  $> 1$  ppm.

The origin of the PGE mineralization is twofold. A primary origin is suggested by the presence of maucherite grains which contain extremely fine-grained myrmekitic native silver intergrowths (primary silver). Generally, drill holes that contain anomalous PGE values also contain this silver-bearing type of maucherite. Since maucherite appears to have formed early in the paragenetic sequence, this suggests that silver (and PGEs) were scavenged from the sulfide melt by maucherite, and thus the PGEs are related to a primary (magmatic) process. However, a hydrothermal origin for the PGEs is also indicated. Anomalous PGE values are commonly associated with Cl-drop encrusted massive sulfide drill core. The spatial distribution of the Cl-drop encrusted drill core also coincides with the EW-trending anticline (Fig 2). Presence of the Cl-drops indicates that the rocks of the Local Boy area were invaded by Cl-bearing solutions that may have been capable of transporting and concentrating PGEs.

Therefore, both primary/magmatic (sulfides injected into a "vein-like" setting) and later secondary/hydrothermal processes appear to have been factors in controlling PGE distribution in the Local Boy area. However, it is difficult to separate the primary and secondary processes. This is due to the coincidence of several features within an EW-trending zone which include: 1) anticline in the footwall rocks; 2) overall massive sulfide distribution; 3) spatial distribution of anomalous PGE values; and 4) spatial distribution of Cl-drop encrusted drill core. Reactivation of structures that controlled the initial "vein-like" massive sulfide distribution could have been responsible for channeling later hydrothermal solutions.

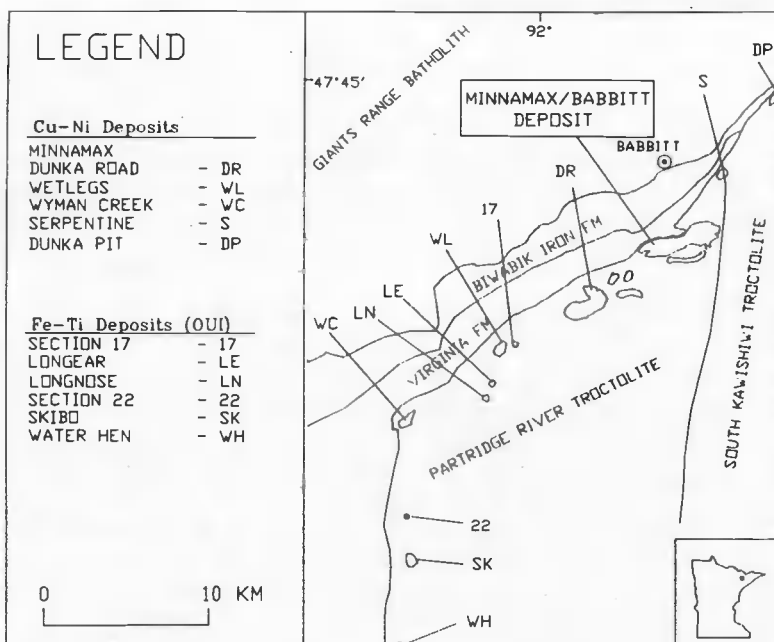


Figure 1: Location of Cu-Ni deposits within the Partridge River Troctolite of the Duluth Complex.

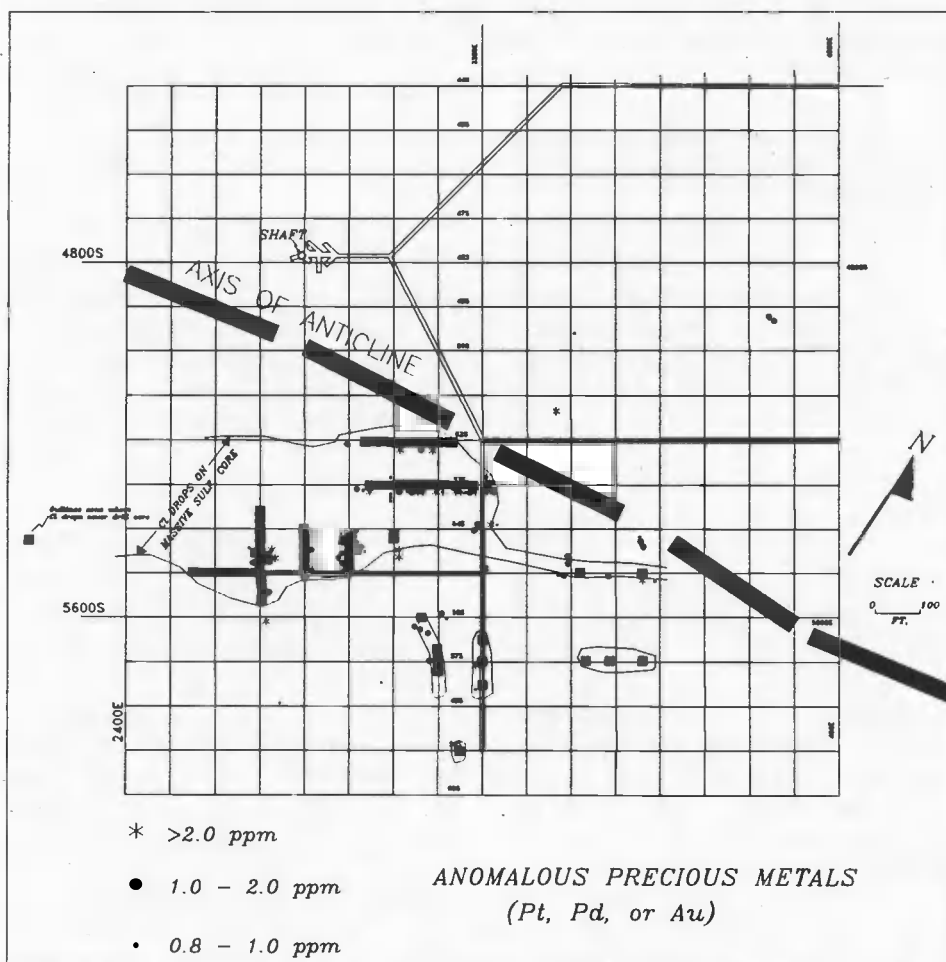


Figure 2: Distribution of anomalous precious metal values and Cl-drop encrusted drill core in the Local Boy area, Minnamax deposit

THERMAL AND REGIONAL METAMORPHISM IN ARCHEAN BASALT,  
BIRD RIVER GREENSTONE BELT, MANITOBA, CANADA

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Abstract

In southeastern Manitoba, on the western edge of the Superior Province (Archean), the Bird River greenstone belt is a small sub-province of supracrustal rocks. Pillow basalts are a lower stratigraphic formation, approx. 2 km thick, overlain by mafic and felsic volcanics and clastic meta-sedimentary rocks. Samples from 3 localities are described with chemical and mineral analyses.

Samples # 1 and 2 have compositions similar to other Archean tholeiites; their flat REE patterns and ratios of Nb-Zr-Y and Ti-Zr-Y are comparable (with exceptions) to MORB. The exceptions are the selvages of the pillows of Sample #2, which are enriched in Y, Fe<sup>+3</sup>, Fe, Mg, Ca, Mn compared to cores and to sample #1. The chemical anomalies are ascribed to diagenetic or hydrothermal alteration, possibly syn-gentic. Sample #3, a cross-cutting dike, is an meta-andesite.

The formations are folded, faulted, and steeply dipping (deformation D2), with a regional foliation S2. There are post-folding shear zones (D3). During metamorphism, hornblende, garnet and cummingtonite have overgrown the main S2 foliation. This indicates that heat flow, probably from the adjacent batholithic intrusion, continued after deformation. This thermal recrystallization is called M3. The samples are in the aureole of a late-tectonic batholith of granite and granodiorite, the Lac du Bonnet (LDB) batholith. We interpret that this batholith is the heat source for M3 recrystallization.

In samples #1 and 2 the compositions of plagioclases are rich in Ca and Al (An 63 - 91), which is anomalous as compared to the compilation of Spear (1981). They are comparable to the calcic plagioclases of the low-pressure calcic schists (garnet-hornblende zone) of the Panamint Mountains (Labotka 1987). The hornblendes are rich in tschermaks molecule, especially #2 selvages. We interpret these compositions as the result of the enhanced instability of epidote at low pressures (andalusite type facies). An additional indicator of low pressures (Yardley 1989) is the abundance of cummingtonite in samples #2 and 3, this is caused by the preference of amphibole to lower its content of Al at low P.

The selvages of the pillows of sample 2 have porphyroblastic garnet, plus small amounts of biotite. Temperatures of M3 are thereby determined as 565 - 600°C (range; additional error may be 50 °). The garnet-hornblende geothermometer of Graham & Powell (1984) gives 575 - 608°C.

The preservation of inclusions of biotite in cores of hornblende

indicates that M2 biotite was a reactant that was used up by the M3 recrystallization.

The thermal metamorphic aureole of a late-tectonic granite in an Archean greenstone belt may be outlined by mapping the appearance of the garnet-hornblende assemblage (without chlorite, as pointed out by Labotka 1987) in the meta-basites. The ability of amphiboles, garnet, plagioclase and epidote to react in the post-tectonic thermal aureole indicates that the late batholiths are the source of advective heat. It remains to be determined whether or not there was a loss of H<sub>2</sub>O, or conditions of  $P_{H_2O} < P_{total}$ , in this environment.

# **A STRUCTURAL ANALYSIS OF THE MIDCONTINENT RIFT IN MICHIGAN, BASED ON A FAULT ARRAY ANALYSIS UTILIZING SLICKENSIDES**

Kathleen M. Witthuhn

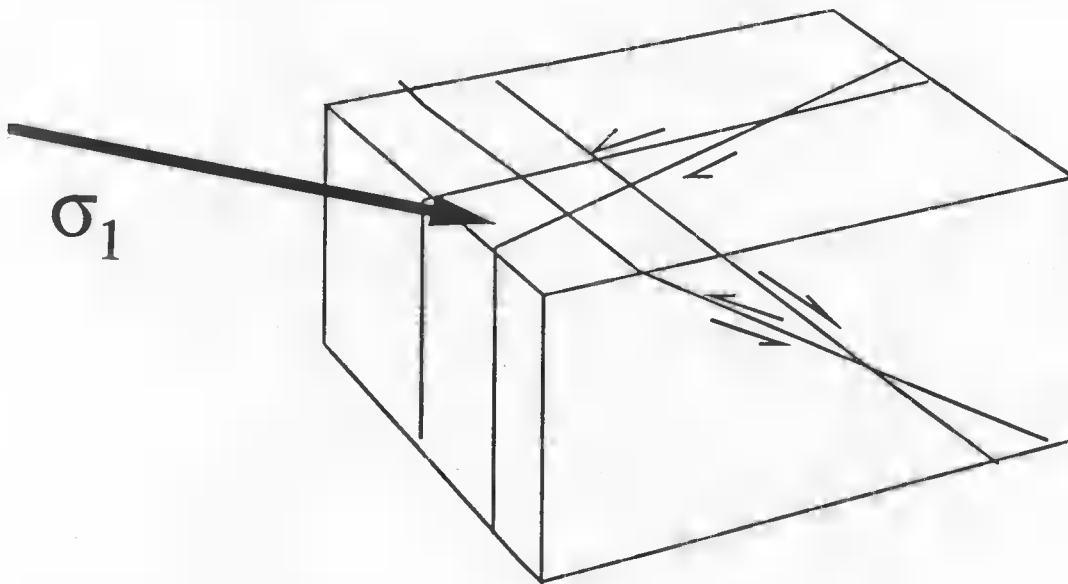
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The Midcontinent Rift is a 1.1 billion year old crustal structure which has been defined primarily by geophysical studies. Many studies have examined the rift from a petrologic view but few have examined the structural geology in any detail. Initial field work in Minnesota, Canada, and the Upper Peninsula of Michigan yielded data on fault and joint populations, from which scattered stress tensors were calculated. Examination of nearly 600 small scale fault structures on both of the synclinal limbs along a transect northwest across the Lake Superior syncline, from the Keweenaw Peninsula to Isle Royale in Michigan, was more successful in isolating two consistent stress fields for each limb of the syncline, that would satisfy criteria for closing of the Midcontinent Rift System. This study evaluates existing models by applying geometrical and statistical methods to the data to determine the kinematics of the closing of the Midcontinent Rift System.

The Keweenawan Portage Lake Volcanics (PLV) form a broad anticline, with an axis just west of Delaware, Michigan, causing the lava flows west of Delaware to trend northeast, while those east of the anticlinal axis trend mainly east-west. A majority of the small scale fault orientation data collected on the east-west trending flows of the Keweenaw Peninsula are parallel with this trend, having steeply pitching slickensides, indicating dip-slip motion on the faults. However, there are two smaller fault populations trending slightly east and west of north, with low angled slickenside orientations, suggesting strike slip motion. All of the fault orientations collected from the northeast trending PLV are parallel with

this orientation and the low angled pitch of the slickensides, also, indicates strike-slip motion along these faults (figure 1).

Figure 1. Diagram of the major fault trends on the Keweenaw Peninsula showing their compatibility with the computed compressive tensor.



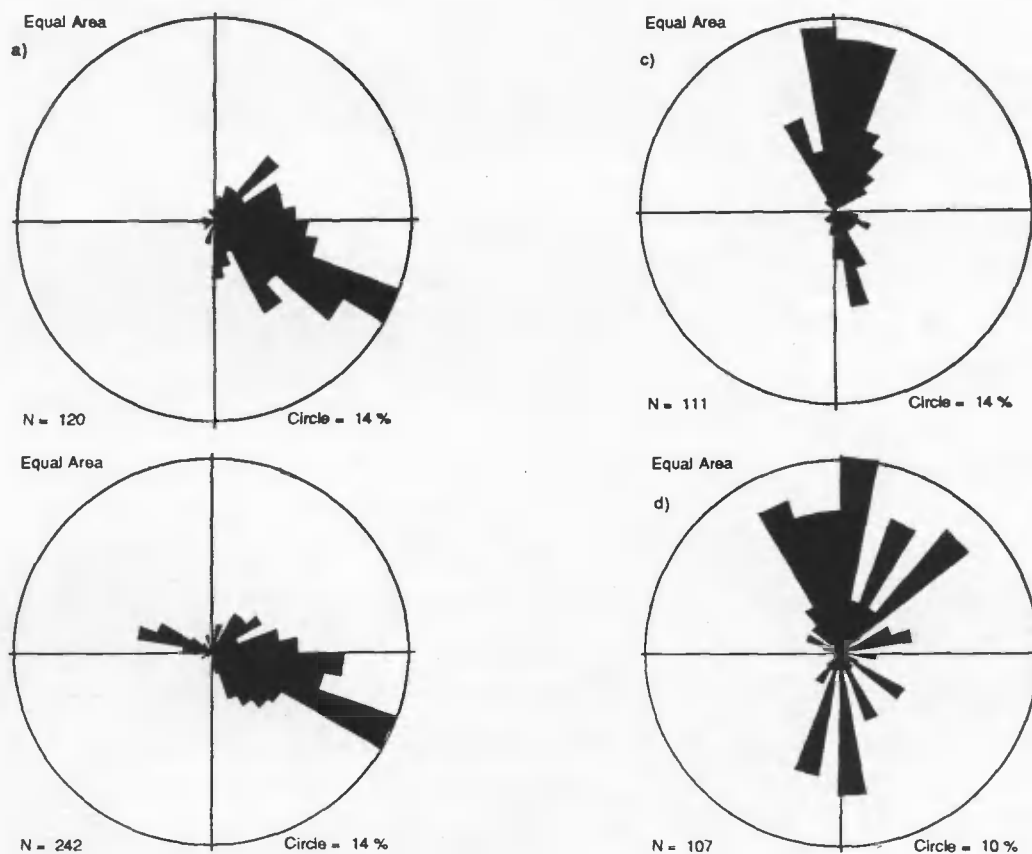
Fault orientation data from Isle Royale, on the north limb of the Lake Superior syncline, exhibited two shallowly dipping populations, one trending northeast and the other northwest, with slickenside lineations suggesting mainly strike slip motion along the faults. The quality of fault sense criteria was excellent, with fault slickenline growths allowing for incontrovertible macroscopic determinations of fault motion.

Implimentation of a fault inversion analysis for data from the Keweenaw Peninsula resulted in a southerly compression, while that from Isle Royale National Park, indicates two tensors, one southerly and the other east-southeasterly compression. These tensors are compatible with a model of southerly extension and compression, introduced by Cambray and Fugita (ILSG, 1991), with the central portion of the Midcontinent Rift containing more material to be compressed than the southwest- and southeast trending limbs to the west and east, respectively. With this in mind, a

southerly compression would lead to an east-west extrusion along the northern limb of the syncline, caused by contact of this limb with the arcuate shoreline of Minnesota and Ontario, Canada, combined. Contact of this sort would modify the local stress field around Isle Royale, on the northern limb, and create a maximum compressive stress in a more easterly direction.

These conclusions are confirmed by examination of the trend of slickensides, from both study areas, which describes the motion on each limb as calculated by the fault array analysis program (figure 2).

Figure 2. Rose diagram of the trend of slickensides on normal and reverse faults on Isle Royale (a and b) and the Keweenaw Peninsula, Michigan (c and d).



# Geochemistry of the Metadiabases in the Republic Mine Area, Northern Michigan

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There are three layers of Precambrian metamorphosed and altered diabase interlayered within the Negaunee iron formation and several other small bodies in the Goodrich quartzite and Precambrian granitic gneiss in the Republic Mine area, which is located at the the core of the Republic syncline in the Marquette synclinorium and in the center of the regional metamorphic zones in Northern Michigan. All the diabases underwent extensive regional pre-tectonic hydrothermal alteration, metamorphism and deformation, and local metasomatism, which resulted in the formation of amphibolite, actinolite schist, cummingtonite or grunerite schist, andalusite schist, muscovite schist and chlorite schist from the center of metadiabases to the contact between the metadiabases and the Negaunee iron formation, and from the limb to keel of the Republic syncline.

That all these rocks are formed from same protolith is suggested by: 1). the stratigraphically conformable relationship between the metadiabases and the Negaunee iron formation, which are identical and uniform in the whole area, 2). the gradual transition between the diabase and amphibolite outside of the Republic Mine, 3). the gradual change of the species and volume of minerals and the mineral assemblages from the center of the metadiabases to the contact between the metadiabases and the iron formation and from the limb to the keel of the syncline, 4). the relict amphibolite bodies in different zones, 5). the existence of relict minerals, such as the relict plagioclase in all the rock types, and the relict andalusite in the muscovite schist and chlorite-garnet schist, 6). the extensive relict textures, such as the relict diabase textures in amphibolite and the pseudomorph of amphibolite from pyroxene, 7). the gradual decrease of Ca, Mg, Na, Sr, V, Cr, Sc, Fe<sup>++</sup>, Th, and Y corresponding to the gradual increase of Al, Ti, K, P, H<sub>2</sub>O, Nb, Zr, Rb, Ni, Ce, La, Fe<sup>+++</sup>, Mn, Si, Co, and Ba of rock bulk chemical composition from the center of metadiabases to the contact between the metadiabases and the iron formation and from the limb to the keel of the Republic syncline, 8). the gradual decrease of anorthite content in the plagioclase and the increase of the Al/Si, Al/Ca, K/Na and Fe/Mg ratios in various amphiboles in these two directions.

The evidence above together with the structural analysis suggest: 1). the extensive regional hydrothermal alteration before the regional metamorphism of the diabase resulted in the decomposition of pyroxene and plagioclase in the diabase and the formation of mafic to peraluminous rocks through the leaching of iron, magnesium, calcium and sodium in the diabbases, 2). these rocks with the different chemical compositions are metamorphosed to amphibolite, actinonite schist, cummingtonite schist, andalusite and muscovite schist, and finally 3). the second episode of hydrothermal alteration resulted in the extensive alteration of these metamorphic rocks and in the local metasomatism at the contact between the metadiabases and Negaunee iron formation. These conclusions are further supported by: 1). the zoning of the garnet in chlorite schist, which is defined by the inner garnet core; the middle altered garnet ring with muscovite, biotite, quartz and chlorite; and the outer garnet rim with distinct overgrowths and well-developed faces; all three garnet zones are then cut by the chlorite veins containing quartz and epidote, 2). the existence of at least three different generation of plagioclase: the relict plagioclase with anorthite content larger than 50, the intergranular recrystallized plagioclase with lower anorthite content, and the plagioclase (most albite) as the inclusions in amphiboles; all of these plagioclase underwent extensive sericitization, 3). the extensive sericitization of andalusite, 4). the gradual decrease of anorthite content from the center to the edge of the relict plagioclase; and the increase of the Al/Si, Na/Ca, K/Na and Fe/Mg ratios from the center to the edge of the amphiboles, 5). the three sample subspaces in the cumulative possibility diagram, in the multi-peak curves of distribution patterns, and in the histograms for all the elements, which suggest at least three geological processes, 6). the Pearce elements ratios which also suggests three possible geological processes and the decomposition of amphiboles and plagioclase as major mechanism for the regionally pre-tectonic hydrothermal alteration, 7). the isocon analysis results which indicate that there are at least three major isocons, which are well demonstrated by two chemographic methods, thus suggesting at least three geologic processes. The detailed calculations to compare the chemical composition and variation between the various rock types and the least altered metadiabase-amphibolite, between adjacent rocks, and between different sections from the limb to the keel of the syncline using isocon analysis method revealed the total mass loss or gain for whole rocks, and the absolute and relative loss or gain for each elements, which also supports the conclusions discussed above. 8). the distinct reflections along all the element concentration curves occur not only from the muscovite schist to the chlorite schist, but also from the amphibole schist to the andalusite schist, which indicates the distinct change of the physical and chemical conditions for the three different geologic processes.

The degree of metamorphism and hydrothermal alteration is partially controlled by the structural position of the metadiabases. Compared to the relatively simple structures on the limb of the syncline, numerous kinds of faults (especially the large-scaled axial faults which cut the keel of the syncline), joints and sliding between layers are well developed in the keel. These structures are the channels through which the hydrothermal fluid has flown through and they mark the position where the most intensive alteration of metadiabases happens. The comprehensive analysis of the above information also suggests that the fluid flow direction runs from the contact between the metadiabases and the iron formation to the center of the metadiabases and that the second episode of hydrothermal activity is a result hydrothermal alteration and local metasomatism rather than of retrograde metamorphism.

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