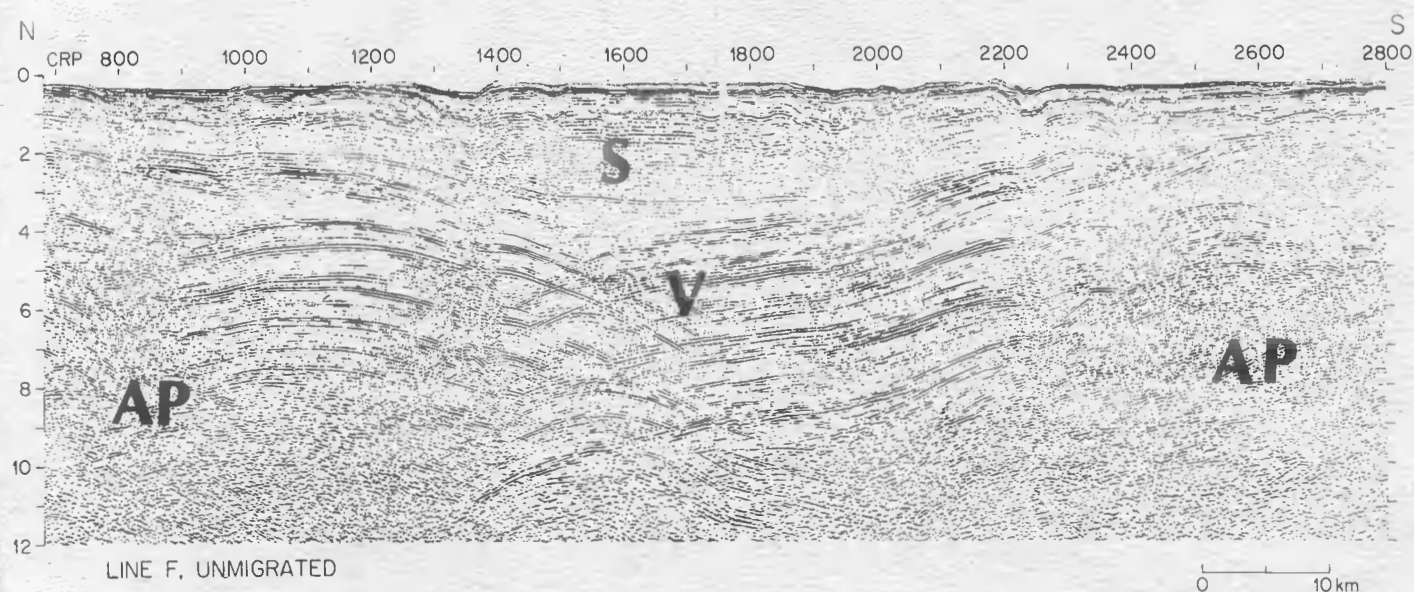
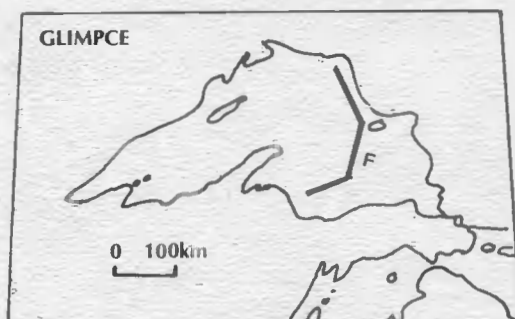


**Thirty-fourth Annual Meeting
Marquette, Michigan
May 12 and 13, 1988**

Institute on Lake  **Superior Geology**

**Proceedings and Abstracts
Volume 34, Part 1**



34th ANNUAL

INSTITUTE ON LAKE SUPERIOR GEOLOGY

Proceedings and Abstracts

Marquette, Michigan

May 12 and 13, 1988

Organized by

John Hughes, Northern Michigan University
John Klasner, Western Illinois University
Klaus Schulz, U. S. Geological Survey

Program Chairman and Editor: John Klasner

Volume 34. Part 1 Program and Abstracts
Part 2 Field Guidebooks

COVER Seismic time section with inset
showing the location of line F
in Lake Superior. The seismic
section is from the GLIMPCE
program in the Great Lakes.
S = sediments; V = volcanics;
AP = Archean-Proterozoic terrane.

PURCHASE OF PROCEEDINGS AND ABSTRACTS AND FIELD GUIDEBOOKS

The Proceedings and Abstract and the Field Guidebooks for the 34th Annual Institute on Lake Superior Geology may be purchased by contacting:

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

PROCEEDINGS AND ABSTRACTS, VOLUME 34. PART 1 ----- \$4.00
FIELD GUIDEBOOKS, VOLUME 34, PART 2 ----- \$5.00

Issues of Proceedings and Abstracts and Field Guidebooks from previous meetings may be purchased by contacting the Secretary-Treasurer:

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

TABLE OF CONTENTS

Institutes on Lake Superior Geology to 1988	i
Constitution of the Institute on Lake Superior Geology	ii
By Laws on the Institute on Lake Superior Geology	iii
Goldich Medal Guidelines	iv
Student Travel Award	v
Board of Directors	vi
Local Committee	vi
Best Student Paper Committee	vi
Goldich Medal Committee	vii
Field Trip Leaders	vii
Technical Session Chairs	vii
Goldich Medal Recipient	viii
Banquet Speaker	viii
Acknowledgements	viii
Report of the Chairs of the 33rd Annual Institute	ix
Calender of Events	xii
Abstracts	xviii

INSTITUTES ON LAKE SUPERIOR GEOLOGY

<u>INSTITUTE NUMBER</u>	<u>DATE</u>	<u>PLACE</u>
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

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

" " " 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 Chairmen; but if the board should at any time consist of less 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 a 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 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. Dues 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 the 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 Board of Directors, I.L.S.G., 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. Their annual nominee will be voted on at the annual business meeting. 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) The Goldich Medal Nominating Committee shall select the medalist and will make its recommendation to the Board of Directors by November 1, of that year.
- 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 May meeting.
- 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 ILSG Student Travel Award to support student participation at the annual Institutes. The awards will be made from the accrued interest 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 and size will be 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.

BOARD OF DIRECTORS

1988

J. S. Klasner (with J. D. Hughes and K. J. Schulz), Department of Geology, Western Illinois University, Macomb, Illinois 61455

1987

R. P. Sage (with E. D. Frey) Ontario Geological Survey, Ministry of Northern Development and Mines, 77 Grenville Street, Toronto, Ontario M7A 1W4

1986

J. K. Greenburg (with B. A. Brown) Wisconsin Geological and Natural History Survey, 3817 Mineral Point Road, Madison, Wisconsin 53705

1985

C. E. Blackburn, Mineral and Development Branch, Ministry of Northern Development and Mines P. O. Box 5160, Kenora, Ontario P9N 3X9

Secretary-Treasurer

J. Kalliokoski, Department of Geology and Geological Engineering, Michigan Technological University, Houghton, Michigan 49931

LOCAL COMMITTEE

J. D. Hughes: Conference Co-Chair; Local arrangements

J. S. Klasner: Conference Co-Chair; Program and Abstracts editor, mailings and registration

K. J. Schulz: Conference Co-Chair; Field trip arrangements and field guidebook editor, banquet speaker

BEST STUDENT PAPER COMMITTEE

G. W. Adams: Noranda Exploration, Rhinelander, Wisconsin

G. L. LaBerge: University of Wisconsin-Oshkosh, Oshkosh, Wisconsin

R. P. Sage: Ontario Geological Survey, Toronto, Ontario

GOLDICH MEDAL COMMITTEE

J. J. Brummer: Brummer Consulting, Toronto, Ontario
K. D. Card: Geological Survey of Canada, Ottawa, Ontario
R. J. Ojakangas: University of Minnesota, Duluth, Minnesota

FIELD TRIP LEADERS

D. A. Baxter: Michigan Technological University, Houghton,
Michigan
T. J. Bornhorst: Michigan Technological University, Houghton,
Michigan
B. C. Boyum: Cleveland-Cliffs, Inc. Ishpeming, Michigan
R. A. Brozdowski: Callahan Mining Corporation, Negaunee, Michigan
C. Gallup: California Institute of Geology, Long Beach,
California
W. R. Gregg: Michigan Technological University, Houghton,
Michigan
R. C. Johnson: Michigan Technological University, Houghton,
Michigan
Wm. Kangas: Cleveland-Cliffs, Inc., Ishpeming, Michigan
J. S. Klasner: Western Illinois University and U. S. Geological
Survey, Macomb, Illinois
M. L. MacLellan: Michigan Technological University, Houghton,
Michigan
R. G. Reed: Michigan Geological Survey, Lansing, Michigan
G. W. Scott: Callahan Mining Corporation, Negaunee, Michigan
P. K. Sims: U. S. Geological Survey, Denver Colorado

TECHNICAL SESSION CHAIRS

R. L. Bauer: University of Missouri, Columbia, Missouri
F. W. Cambray: Michigan State University, Lansing, Michigan
W. F. Cannon: U. S. Geological Survey, Reston, Virginia
W. J. Hinze: Purdue University, West Lafayette, Indiana
M. M. Kehlenbek: Lakehead University, Ontario

S. W. Nicholson: Washington, D. C.

J. M. Paces: Michigan Technological University, Houghton,
Michigan

D. Southwick: Minnesota Geological Survey, Minneapolis,
Minnesota

GOLDICH MEDAL RECIPIENT

Walter S. White, U. S. Geological Survey (retired). Medal
awarded by D. M. Davidson, Northern Illinois University

BANQUET SPEAKER

P. F. Hoffman: Geological Survey of Canada, Ottawa, Ontario

ACKNOWLEDGEMENTS

Several people and organizations assisted in preparation of the 34th Annual ILSG. Without their help the many tasks in preparing this meeting could not have been done. We would like to thank the following people and organizations for their help.

Diana Robertson and the office of Non-Residential Programs at Northern Michigan University for logistical assistance.

The Department of Geography, Earth Science, Conservation and Planning at Northern Michigan University

The Department of Geology at Western Illinois University

Gretchen Klasner for assistance in handling finances.

Cathy McCormick and Corrine Weaver for help with typing, logistics, and mailing.

Callahan Mining Corporation for assistance with field trips.

Michigan Technological University for assistance with transportation for field trips.

Minnesota Geological Survey for providing mailing lists and labels

33rd INSTITUTE ON LAKE SUPERIOR GEOLOGY
WAWA, ONTARIO - 1987

The 33rd meeting of the Institute on Lake Superior Geology was held in Wawa, Ontario from 10 to 15 May 1987. The meeting was hosted by the Ontario Ministry of Northern Development and Mines - Wawa Resident Geologist Office and the Ontario Geological Survey. Technical sessions were held on 12 and 13 May in the community arena and posters were displayed in the adjacent curling clubhouse. Registered attendance was 255, including 30 students. Pre-registration totalled 220.

Four pre-meeting, three repeated post meeting, and two duplicate field trips during the meeting attracted a total of 245 participants, many attending two of the five individual tours. Bernie Schnieders became an excellent substitute for Tom Muir when illness forced Tom's absence from leadership of a review of Hemlo geology attended by 47. John Percival conducted two 2-day transects of the Kapuskasing Structural Zone for 40 visitors. Ron Sage led 33 participants through the stratigraphy of the Michipicoten Iron Formation on two field trips. Wawa Area Gold Mineralization was examined by 96 during two field trips led by Ed Frey. Staff of the G.W. MacLeod siderite mine of the Algoma Steel Corporation hosted 29 visitors on two half-day tours. Separate guidebooks were published for three of the field trips and a fourth is in preparation for the Wawa gold tour. A guidebook was not published for the MacLeod Mine tour.

Thirty-three papers were presented orally and 29 posters were displayed during the technical sessions. M. Lockwood replaced the last-minute cancellation of two papers by R. Dahl, et al., with an impromptu review of chloritoid alteration in the Wawa area. Fifteen students presented eight papers and eight posters and provided a challenging task for the Student Awards Committee. Tony Andrews presented the Best Student Paper Award to Matthew E. Bidwell, Univ. of Wyoming, for his paper "A two-stage simple-shear model for high flattening strains in shear zones of the central Vermillion district, northeastern Minnesota". R.L. Bauer, Univ. of Missouri, was co-author. The Best Student Poster Award went to Kevin M. Sikkila, Michigan Tech. Univ., for his poster "A structural analysis of Proterozoic metasediments, northern Falls River, Baraga County, Michigan", co-authored by W.J. Gregg, Michigan Tech. Univ. Each award consisted of \$150.00 provided from registration fees. Six students received waiver of registration fee and \$50.00 each as a Student Travel Award. These funds also were provided by registration receipts.

The annual banquet on 12 May at the Union Hall was an outstanding feast, catered for 229 people by the Voyageur Restaurant. Allan Goodwin presented the Goldich Medal to Henry Halls, Erindale College-Univ. of Toronto. The guest speaker was Howard Poulsen, Geological Survey of Canada, who reviewed the relationship between tectonics and gold mineralization throughout Canada.

The ILSG Board of Directors held a luncheon meeting on 12 May. In attendance were Co-chairmen Ed Frey and Ron Sage, Bruce Brown, Charlie Blackburn, Gene LaBerge, and Fred Kehlenbeck. Also present were Ted Bornhorst and the 34th ILSG team of John Klasner, John Hughes and

Klaus Schulz. The Board took the following action:

1. As of 2 April 1987 the U.S. account totalled \$3063.21 and the Goldich Medal Fund was \$1153.92. As of 12 May 1987 the Canadian account total was \$5507.61. The 32rd ILSG submitted \$3839.56 (\$2637.56 profit) to the Canadian account in Dec. 1987 and C\$255.00 to the Goldich Medal Fund.
2. Ted Bornhorst moved that the custodian of the Canadian account be present at all business meetings. Motion passed unanimously.
3. Gene LaBerge moved that interest on the combined U.S. and Canadian accounts be used for Student Travel Awards. Motion passed unanimously. It was noted that it is desirable to have \$10,000. in each account and that no meeting should be planned to lose money.
4. The ILSG is a non-profit organization under U.S. law and donations are tax deductible. This fact should be noted on all circulars for U.S. meetings.
5. There is no need to publish the by-laws of the organization for each meeting.
6. Student paper and poster awards should be \$150.00 each, in the currency of the meeting site. The awards should be part of the meeting budget. Co-authored papers are now acceptable, provided that the student is the senior author.
7. Ted Bornhorst and Charlie Blackburn prepared guidelines for Student Travel Awards that were accepted by the Board. Klaus Schulz recommended that the new awards requirements be sent to interested geology departments.
8. The Proceedings and Abstracts volume and field trip guidebooks now have volume and part numbers to allow proper library indexing. The P. & A. title has been standardized.
9. Dr. J.J. (Joe) Brummer, consulting geologist, Toronto, is the new member of the Goldich Medal Committee, replacing W.A. Bodwell.
10. The 1988 ILSG will meet in Marquette, Michigan and will be organized by John Klasner, John Hughes, and Klaus Schulz. The 1989 ILSG will be in Duluth, Minnesota and chaired by Dick Ojakangas. The 1990 meeting may be in Thunder Bay, Ont.
11. Gene Laberge will prepare a certificate for the Best Student Paper & Poster Awards and send them to the winners. The certificate will state title of paper/poster, date, and ILSG location and will be signed by the award committee. The winners' names should be published in the Chairman's report.

Chairing the 33rd ILSG has been an education in organization. We hope that the Wawa meeting has demonstrated that small communities with sufficient accommodations can host future ILSGs. The absence of custom

facilities inspired innovation here, as it can elsewhere.

We again thank all who made the Wawa meeting possible and those who provided encouragement and support. The ILSG is a priceless gathering of friends in the geological fraternity working in the Lake Superior region. We know of no better way to keep in touch with new ideas on the region than through the ILSG.

Respectfully submitted,



E.D. Frey
Wawa, Ontario



R.P. Sage
Toronto, Ontario

Co-Chairmen, 33rd ILSG
January 1987

CALENDER OF EVENTS

AND

PROGRAM

PRE-MEETING FIELD TRIPS

TUESDAY, May 10, 1988

8:00 a.m. to 5:00 p.m.

Field Trip 1 -- Archean geology and mineralization of the
Marquette Greenstone Belt (day one of a two-day
field trip)

WEDNESDAY, May 11, 1988

8:00 a.m. to 5:00 p.m.

Field Trip 1 -- Archean geology and mineralization of the
Marquette Greenstone Belt (day two of a two-day
field trip)

8:00 a.m. to 5:00 p.m.

Field Trip 2 -- Marquette Mineral District of Michigan: Mining
history and geology

REGISTRATION AND WELCOME GET TOGETHER

WEDNESDAY, May 11, 1988

4:00 p.m. to 7:00 p.m.

Registration at the Ramada Inn Convention Center

7:00 p.m.

Welcome get together, poster displays, cash bar.

TECHNICAL SESSIONS

THURSDAY, May 12, 1988

Morning

Geology of the Keweenawan Rift

Co-Chairs: William J. Hinze and James B. Paces

8:15 a.m.

Welcoming remarks

8:20 a.m.

W. F. Cannon

A. G. Green

D. R. Hutchinson

J. C. Behrendt

Variations in structural style
of the Midcontinent Rift
beneath Lake Superior

8:40 a.m.

S. W. Nicholson

J. B. Paces

W. F. Cannon

Development of the Midcontinent
Rift in the Lake Superior
region: Petrologic and
geochemical constraints for a
tectonic model

9:00 a.m.	J. B. Paces D. W. Davis	Implications of a high precision U-Pb age dates on zircons from Portage Lake volcanic basalts on Midcontinent Rift subsidence rates, lava flow repose periods, and magma production rates
9:20 a.m.	K. W. Klewin J. H. Berg	Chemostratigraphy of the lower division lavas of the Mamainse Point Formation and implications for rifting tectonics
10:00 a.m.		Coffee break
10:20 a.m.	C. P. Ervin J. F. Olmsted M. G. Mudrey, Jr.	Geophysical and petrological characteristics of the Clam Lake intrusion -- a constraint on the time of Keweenawan basin development
10:40 a.m.	R. P. Meyer W. V. Green	Comparison of the Keweenawan and Gregory Rifts from the study of teleseismic delay times and Bouguer gravity
11:00 a.m.	M. G. Mudrey, Jr. A. B. Dickas	Midcontinent Rift model based upon Gregory Rift tectonic and sediment geometries
11:20 a.m.	P. A. Nielsen	The Keweenawan Rift: a kinematic model for its origin and evolution
11:40 a.m.		Lunch. Board of Directors luncheon

THURSDAY, May 12, 1988
Afternoon

Geology of the Keweenawan Rift/Miscellaneous

Co-Chairs: W. F. Cannon and S. W. Nicholson

2:00 p.m.	F. W. Cambray	A tectonic model for the Midcontinental Rift System
2:20 p.m.	M. L. Manson* H. C. Halls	A submersible dive on Superior Shoals: plans and prospects
2:40 p.m.	W. J. Hinze W. C. Kelly	Scientific drilling into the Midcontinent Rift System
3:00 p.m.		Coffee break

3:20	p.m.	V. W. Chandler R. J. Ferderer	Copper-nickel mineralization of the Duluth Complex, northeastern Minnesota, a gravity and magnetic perspective
3:40	p.m.	B. Saini-Eidukut*	Sulfide mineralization and associated hydrous silicates in anorthositic rocks from the Duluth Complex
4:00	p.m.	M. T. Lewchuk* D. T. A. Symons	Paleomagnetism of the Clay-Howells carbonatite and Keweenawan motion on the KSZ
4:20	p.m.	M. D. Thompson* C. P. Ervin	Refraction analysis of the GLIMPCE marine reflection profile in Georgian Bay
4:40	p.m.	W. Jarvis J. Kalliokoski	Michigan kimberlite province
5:00	p.m.	T. J. Boerboom	An unusual apatite-rich nelsonite-, pyroxenite-, and hornblendite-bearing intrusion of post-Penokean age, central Minnesota
5:30	p.m.		Cash Bar
6:30	p.m.		Banquet

FRIDAY, May 13, 1988

Morning

Geology and mineral deposits of Archean rocks

Co-Chairs: R. L. Bauer and M. M. Kehlenbeck

8:20	p.m.	T. J. Bornhorst	An introduction to the geology and mineral deposits of the Archean Marquette Greenstone Belt, Michigan
8:40	a.m.	G. B. Margeson J. W. Norby R. A. Brozdowski A. S. Carter B. A. Bouly	Comparison of two parts of the Dead River-Ishpeming Greenstone Belt: evidence for correlation of volcanic stratigraphy
9:00	a.m.	J. W. Norby	History of precious metal exploration/development in the Dead River-Ishpeming Greenstone Belt
9:20	a.m.	R. L. Bauer	Multiple folding and regional fold patterns in the northern Vermilion granitic complex, NE Minnesota

9:40 a.m.	J. R. Tabor* P. J. Hudleston	Deformation history of the Quetico metasediments along the northern margin of the Vermilion granitic complex, northern Minnesota
10:00 a.m.		Coffee break
10:20 a.m.	B. L. Brasaemle*	Stratigraphy and geobarometry of monzodiorites from the Giants Range Batholith, northeastern Minnesota
10:40 a.m.	G. J. Hudak*	The stratigraphy and physical volcanology associated with the F-group volcanogenic massive sulfide deposits, Sturgeon Lake, northwestern Ontario
11:00 a.m.	M. M. Kehlenbeck B. E. Seemayer	A late Archean clastic sequence-fill of a fault-bounded basin structure
11:20 a.m.	P. Sarvas G. J. Borradaile	The magnetic fabric and structure of the Quetico slates at the Quetico-Wabigoon interface, northwest Ontario
11:40 a.m.		Lunch

FRIDAY, May 13, 1988

Afternoon

Geology of Early Proterozoic Rocks/
Miscellaneous

Co-Chairs: F. W. Cambray and D. L. Southwick

1:00 p.m.	P. K. Sims K. J. Schulz Z. E. Peterman W. R. Van Schmus	Evolution of the Early Proterozoic Wisconsin magmatic terrane of the Penokean orogen
1:20 p.m.	P. F. Hoffman	Animikie Group: A Penokean foredeep?
1:40 p.m.	D. L. Southwick G. B. Morey	Tectonic imbrication and foredeep development in the Penokean orogen, east-central Minnesota
2:00 p.m.	S. D. Stahl D. J. Matty	Early Penokean deformation in the Peavy Pond area, northern Michigan: evidence from the Michigamme Formation and the Peavy Pond igneous complex
2:20 p.m.	J. S. Klasner R. W. Ojakangas K. J. Schulz G. L. LaBerge	Evidence for development of an Early Proterozoic overthrust-nappe system in the Penokean orogen of northern Michigan

2:40 p.m.	J. C. Palmquist	Archean and Proterozoic tectonics-northern Michigan, a speculative synthesis
3:00 p.m.		Coffee break
3:20 p.m.	G. L. LaBerge J. S. Klasner	The Baraboo Quartzite: A new look at an old problem
3:40 p.m.	P. K. Sims Z. E. Peterman J. S. Klasner	The Mountain shear zone -- relevance to age of quartzite at McCaslin and Thunder Mountains, northeastern Wisconsin
4:00 p.m.	W. T. Jolly	Geochemical stratigraphy of the Huronian continental volcanics, Ontario: Relative contributions of mantle heterogeneity, open-system magmatism and crystal fusion
4:20 p.m.	A. U. Falster W. B. Simmons	Emplacement, mineralogy, and internal evolution of a highly evolved Li-pegmatite in Florence County, Wisconsin
4:40 p.m.	B. H. Boyum	The origin and extent of the hard and soft iron ores of the Maquette Range, Michigan

* Papers eligible for student competition

POSTER PAPERS

The authors of poster papers have been requested to be at their poster displays during the first part of the lunch breaks on Thursday and Friday and at the end of the technical sessions on Thursday.

- C. D. Anderson and R. Argenal -- New VLF-EM field parameters
- D. A. Baxter* and T. J. Bornhorst -- Multiple discrete mafic intrusions of Archean to Keweenaw age, western Upper Peninsula, Michigan
- T. M. Bodus* and W. F. Kean -- Preliminary paleomagnetic study of the Amberg and Athelstane granites in northeastern Wisconsin
- M. Cohen*, J. Mancuso, J. Frizado, and D. Stewart, E. Berdusco -- Paragenetic relationships among siderite, magnetite, calcite, quartz, and sulfides in the MacLeod Siderite Mine, Wawa, Ontario
- D. M. Davidson, Jr. -- Precambrian Red Bluff granite complex, West Texas: Comparison with other Mid-Proterozoic rapakivi granites

- J. Feeny* and W. F. Kean -- Paleomagnetism of Keweenawan age basalts from the Taylor Falls-St. Croix Falls area of Wisconsin and Minnesota
- R. J. Ferderer* -- Application of Werner deconvolution to the Penokean fold-and-thrust belt, east-central Minnesota
- J. Fronk* and D. C. Stewart -- An investigation into the chemical processes causing the formation of unakite in the Waupaca adamellite of Wisconsin
- T. M. Han -- Genesis and metamorphism of magnetite in Biwabic Iron-Formation, Mesabi District, Minnesota
- P. K. Jongewaard* -- Stratigraphy and physical volcanology of the footwall rocks to the Sturgeon Lake massive sulphide deposits, NW Ontario
- M. L. MacLellan* and T. J. Bornhorst -- Geology, structure and mineralization of the Reany Lake area, Marquette County, Michigan
- M. G. Mudrey, Jr., and B. A. Brown -- Bedrock geology of the Superior map sheet, Wisconsin
- J. W. Peterson* and C. A. Geiger -- Two generations of garnet growth in the Hardwood gneiss, Dickinson County, Michigan
- R. Schneiker* and W. F. Kean -- A paleomagnetic study of the Hamilton Mound area of Adams County, central Wisconsin
- K. J. Schulz, P. K. Sims, and Z. E. Peterman -- A post-tectonic rare-metal-rich granite in the southern complex, Upper Peninsula, Michigan
- J. R. Small* and T. J. Bornhorst -- The Reany Creek Formation, northern Marquette County, Michigan: Archean or Proterozoic?
- P. J. Wagner and M. K. Sood -- Geochemistry and petrology of the Athelstane granite, Marinette County, Wisconsin
- S. M. Wee and J. T. Wilband -- Geochemistry and tectonic significance of Early Proterozoic igneous rocks, northern Michigan and northeastern Wisconsin
- J. L. Welsch -- Preliminary structural analysis of Archean rocks in the Virginia Horn area, northeastern Minnesota

* Papers eligible for student competition

POST MEETING FIELD TRIP

SATURDAY, May 14, 1988

8:00 a.m. to about 7:00 p.m.

Field Trip 3 -- Evidence for Early Proterozoic overthrusting in northern Michigan and Wisconsin. This field trip terminates in Iron Mountain, Michigan, which has air service. The bus will return to Marquette.

ABSTRACTS

NEW VLF-EM FIELD PARAMETERS
by

Chris D. Anderson and Roger Argenal
Winnipeg, Manitoba, Canada

The primary field from the VLF transmitter and the secondary field from a conductor combine at a location resulting in a EM field ellipse. Conventional measurements are of the angle the major axis of the ellipse makes with a horizontal plane (sometimes called the in-phase measurement) and the ratio of the minor and major axes of the field ellipse expressed as percent (sometimes called the out-of-phase or quadrature measurement). In place of the ratio measurement, some systems measure the secondary field strength which often is expressed as a percent above the primary field.

Based on field experience and model calculations we have found that the measurement of the direction of the horizontal component of the secondary field gives a good indication of the strike of the conductor. That is, the direction without a secondary field is at right angles to the direction to the VLF station. With the presence of a strong secondary field, the direction will be controlled by the conductor and will be at right angles to the strike of the conductor. For moderate secondary fields, the effect can be evaluated and using this information the strike of the conductor can be calculated. This procedure is particularly important in areas of multiple conductors.

In the case of three field vectors at a station, namely, the primary field, a strong secondary field from a bed rock conductor, and a secondary field from overburden having mostly a quadrature component, the calculations and results from field and model data clearly show the limitations of using the ratio data in interpretation.

Finally, the results of multiple-conductor end effects and non-planar field vectors result in a triaxial field ellipsoid which can be partially resolved as of the interpretation.

MULTIPLE FOLDING AND REGIONAL FOLD PATTERNS
IN THE NORTHERN VERMILION GRANITIC COMPLEX, NE MINNESOTA

Robert L. Bauer

Department of Geology, University of Missouri
Columbia, Missouri 65211, USA

The western Vermilion Granitic Complex of the southwestern Quetico Subprovince is a highly deformed amphibolite facies (M_1) migmatite complex. The principal rock units are paragneiss and biotite schist that contain variable concentrations of veins and lenses of early tonalite-granodiorite and younger granite of the adjacent Lac La Croix batholith. These granitic units are interlayered with biotite schist on scales as great as several kilometers and are folded along with the schist into a series of easterly trending folds. The distribution of these folds has been well established by reconnaissance geologic mapping (Southwick and Ojakangas, 1979) and more recently by regional aeromagnetic patterns (Chandler, 1983).

Analysis of multiple fold geometries along the northern margin of the Vermilion Granitic Complex, in the Kabetogama and Namakan Lakes area, indicates that the large-scale regional fold patterns observed in the complex correlate with the youngest of three periods of folding. The oldest deformation produced a strong bedding-parallel foliation (S_1) in the schist and local sinistral/north-side-down shear parallel to S_1 . Well-developed asymmetric pull-apart structures in early tonalite veins parallel to bedding in the schist indicate the kinematics of shear.

The second deformation generated easterly plunging F_2 folds and a D_2 LS fabric that locally aligns M_1 sillimanite-muscovite tufts parallel to a D_2 axial plane foliation (S_2) and F_2 fold hinges. In the migmatitic rocks described here, the F_2 folds are of S-symmetry and fold the D_1 asymmetric pull-apart structures and S_1 foliation. Further to the north, in the less migmatitic biotite schist north and west of Kettle Falls, the F_2 folds are of Z-symmetry (Tabor, this volume) and indicate the presence of a major upright east-west-trending F_2 antiformal trace along the Kabetogama peninsula between Rainey and Kabetogama Lakes. Stratigraphic tops are invariably to the north on the southern (migmatitic) limb of this major F_2 structure and change to the south on the northern limb, indicating a downward structural facing of the regional F_2 antiformal syncline (Fig. 1).

F_2 fold axial planes, which are steeply dipping along the northern margin of the complex, dip more gently to the north as one proceeds to the south toward the more migmatitic part of the complex. Here the F_2 folds of S-symmetry are refolded by upright F_3 folds of Z-symmetry on the northern limb of one of the large east-west-trending, easterly plunging antiformal structures recognized during reconnaissance mapping (Fig. 2). An intense D_3 linear fabric occurs parallel to the regional F_3 fold hinges, and a locally well-developed S_3 crenulation foliation deforms both S_1 and the M_1 sillimanite-muscovite tufts aligned in S_2 .

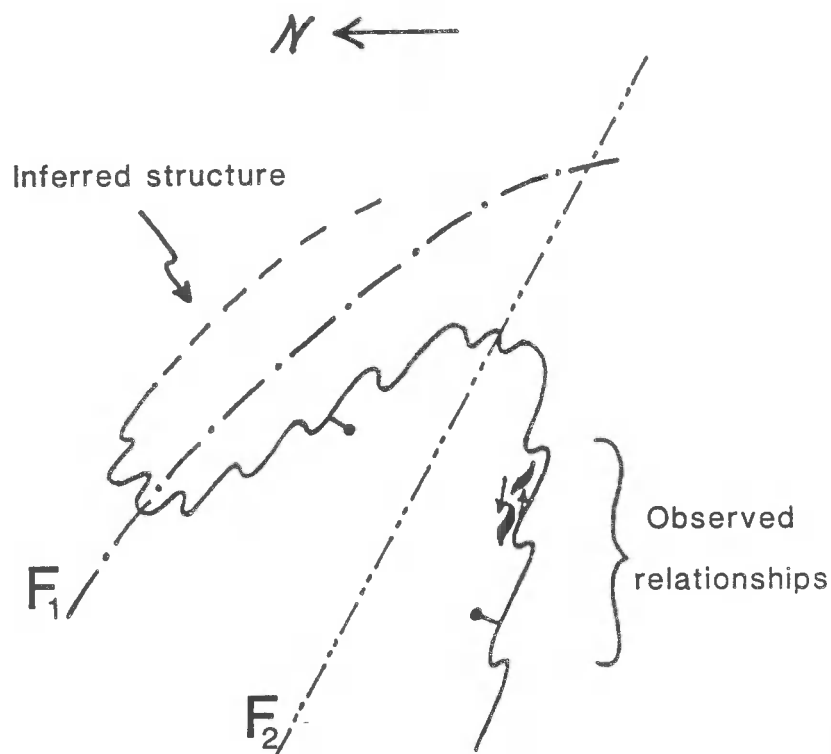


Fig. 1 Schematic cross section illustrating the relationship among F_2 folding, inferred F_1 folding, and stratigraphic younging directions (given by bar and ball symbols).

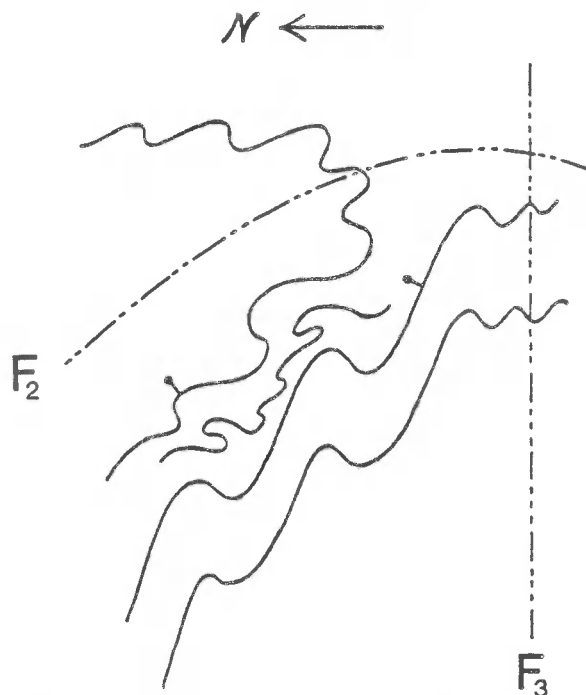


Fig. 2 Schematic cross section illustrating the relationship between F_2 and F_3 folding. This section is south of the cross section shown in Figure 1.

Preliminary analysis of this deformation sequence and the orientation of the structures generated suggests the following sequence of events: Northwest-directed compression resulted in early recumbent folding. Associated northwest-directed shear on the lower limb of this structure produced the asymmetric boudins with sinistral/north-side-down displacement. Continued north- to northwest-directed compression lead to F_2 refolding of the lower (overturned) F_1 fold limb and resulted in the downward-facing easterly plunging F_2 folds. Progressive overturning of these F_2 folds to the south (possibly during emplacement of the Lac La Croix batholith), in a regime of continued north to northwest-directed compression, lead to F_3 refolding of F_2 folds about a similar easterly plunging axis.

A significant feature of this sequence of deformation is its development in a relatively constant north- to northwest-directed compressional regime.

REFERENCES CITED

- Chandler, V.W., 1983, Aeromagnetic map of Minnesota, St. Louis County, total intensity anomaly. Minnesota Geological Survey, Aeromagnetic Map Series, Map A-2, St. Paul, scale 1:250,000.
- Southwick, D.L. and Ojakangas, R.W., 1979, Geological map of Minnesota: International Falls sheet. Minnesota Geological Survey, St. Paul, scale, 1:250,000.
- Tabor, J.R., this volume, Deformation history in the Quetico metasediments along the northern margin of the Vermilion Granitic Complex, NE Minnesota.

**Multiple Discrete Mafic Intrusions of Archean to
Keweenaw Age, western Upper Peninsula, Michigan**

D.A. BAXTER and T.J. BORNHORST (Department of Geology and Geological Engineering, Michigan Technological University Houghton, MI 49931)

The Precambrian bedrock of the western Upper Peninsula of Michigan contains gabbro and diabase intrusions of varying age, origin, and size. Previous studies have typically assigned these mafic rocks, on the basis of alteration and orientation, to one of three broad age groups: Archean, Lower Proterozoic, and Middle Proterozoic (Keweenaw). In contrast, detailed mapping by Kantor (1969) documented more than three ages of mafic intrusions in the Sugarloaf Mountain area, north of Marquette. In this study, we suggest that at least six separate intrusive events occurred based on careful examination of textures, mineralogy, and degree of metamorphism in hand sample, thin section, and outcrop (Figure 1). The local geologic setting of each body must also be taken into consideration.

The oldest mafic intrusions in the region are dike and sill-like gabbro bodies within the Marquette Greenstone Belt. The gabbro typically consists of plagioclase, amphibole, and varying amounts of secondary sericite and retrograde chlorite. The gabbro and volcanic rocks of the greenstone belt are cut by gneissic tonalite to granodiorite plutons which are in turn cut by thin discontinuous, tabular, amphibolite bodies such as those at Wetmore Landing. Although xenoliths of greenstone belt mafic rocks exist in the plutons, we interpret these tabular bodies as mafic intrusions based on the appearance of their margins. Foliation in these dikes is parallel to the surrounding gneissic rocks which leads to the conclusion that the dikes pre-date an Archean deformation event but post-date the tonalite to granodiorite plutonic activity.

The next mafic intrusive activity occurred in a span of time bracketed by the Archean deformation event and the deposition of the sediments of the Lower Proterozoic Marquette Supergroup. These dikes are porphyritic and typically trend north-south ($\pm 12^\circ$). They contain $\frac{1}{4}$ to 3 cm ($\frac{1}{4}$ to 1 inch) euhedral to subhedral phenocrysts of plagioclase (approx. An_{70}). The dikes range from 9-60 meters (30-200 feet) in width and are variably metamorphosed. Cannon (1975) noted that some dikes in the Republic area are distinctly porphyritic and cut the Archean granites and gneisses, but do not cut the Early Proterozoic sediments. Puffett (1975) also noted the existence of coarsely porphyritic mafic dikes which may be Archean in age. We tentatively interpret these porphyritic mafic dikes as equivalent to the Archean Matachewan Dike swarm of Ontario which have an age of 2690 ± 93 Ma (Gates and Hurley, 1973). Condie and others (1987) state that Matachewan dikes in Ontario cut Archean lithotectonic trends and are consequently younger than the last major Archean tectono-thermal event in the area. This is consistent with our observations in the western Upper Peninsula of Michigan. The Matachewan dikes are cut by both Lower Proterozoic and Middle Proterozoic (Keweenaw) diabase dikes on Sugarloaf Mountain (Kantor, 1969). This mafic intrusive event may include some relatively non-porphyritic dikes as well.

Following the deposition of most of the Lower Proterozoic Marquette Supergroup, a swarm of fine- to coarse-grained gabbro and diabase intrusives cut all pre-existing rocks. These dikes and sills have been previously interpreted as related to the Clarksburg Member of the Michigamme Formation (Cannon, 1974). They consist of pyroxene/hornblende, chlorite, plagioclase, epidote, sericite, and variable amounts of secondary carbonate. Intrusive bodies range from 10 cm to over 175 meters (6 inches to > 500 feet) thick but orientation is highly variable, and therefore not useful as a tool for identification. These intrusions are Early Proterozoic in age and have been deformed and metamorphosed during the Penokean orogenic event.

In Marquette County, there are at least two groups of Keweenawan diabase dikes. The older of these is a set of fine-grained diabases that trend approximately north-south ($\pm 15^\circ$). They commonly consist of slightly altered pyroxene, plagioclase, amphibole, and chlorite, and are generally less than 30 meters (100 feet) thick. The younger intrusives trend east-west ($\pm 10^\circ$), cross-cut the older Keweenawan diabase, are medium to coarse-grained, and can be over 200 meters (600 feet) thick. The younger dikes also have a strongly reversed remnant magnetization, and occasionally have a coarse-grained granophyric interior. Cannon (1975) mentioned the existence of "undeformed" diabase dikes which cut the folded sediments of the Marquette Supergroup and also cut the Lower Proterozoic dikes and sills which intrude the sediments. We interpret these undeformed dikes as early (north-south) Keweenawan mafic intrusions.

There are multiple ages of mafic intrusive rocks in the western Upper Peninsula. We propose three distinct groups of Archean mafic intrusives: 1) post-volcanic/pre-plutonic; 2) post-plutonic/pre-deformation; and 3) post-deformation/pre-Early Proterozoic sedimentation (Figure 1). This is followed by intrusives of Early Proterozoic age and by two ages of Keweenawan (north-south and then east-west) intrusives. Previously, the youngest Archean, the Early Proterozoic, and the oldest Keweenawan (north-south) were combined together as the Metadiabase of Early Proterozoic age (Clark and others, 1975; Cannon, 1975; Cannon, 1974; Gair and Thaden, 1968; Puffet, 1974). It is not possible to base a field determination of age simply on the trend of individual intrusives or the degree of alteration and deformation. For example, a N-S trending dike which is known to be Keweenawan in age contains alteration of the primary mineralogy to chlorite, carbonate, and sericite and has weakly foliated margins (Owens, 1986). These preliminary results are being confirmed with further laboratory and field work. This study was partially funded by a grant from the Michigan Geological Survey.

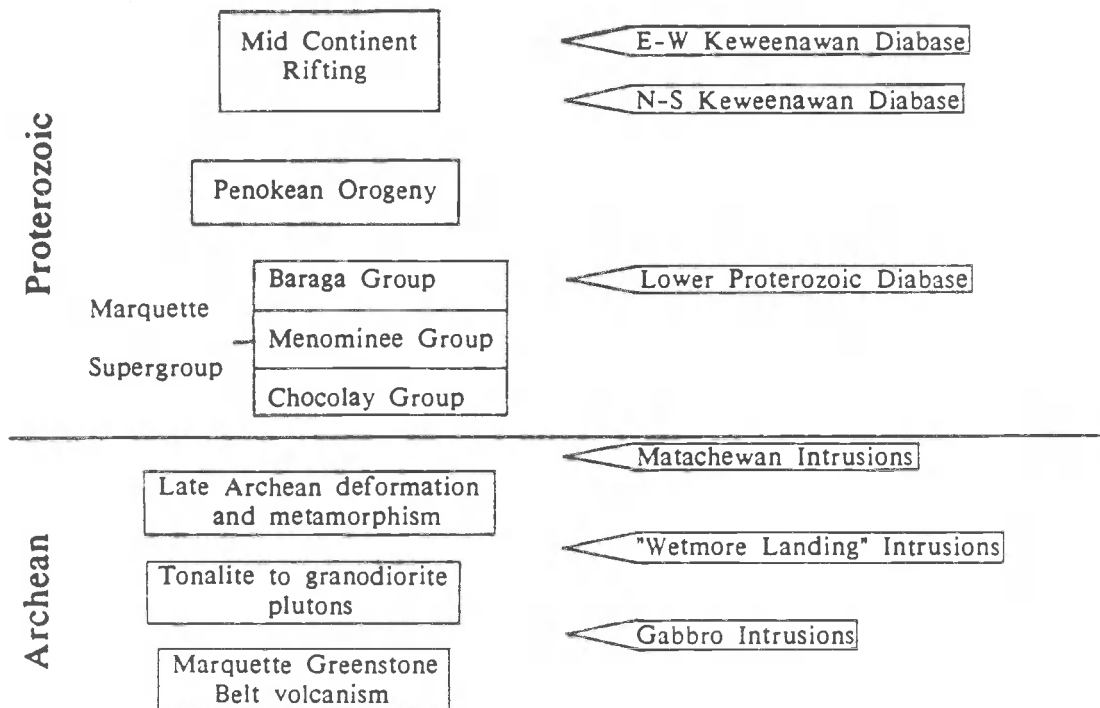


Figure 1. Schematic diagram of mafic intrusion relative chronology.

REFERENCES

- Cannon, W.F., 1975, Bedrock Geologic Map of the Republic Quadrangle, Marquette County, Michigan: U.S. Geological Survey, Miscellaneous Investigations Series Map, I-862.
- Cannon, W.F., 1974, Bedrock Geologic Map of the Greenwood Quadrangle, Marquette County, Michigan: U.S. Geological Survey, Geologic Quadrangle Map, GQ-1168.
- Clark, L.D., Cannon, W.F., and Klasner, J.S., 1975, Bedrock Geologic Map of the Negaunee SW Quadrangle, Marquette County, Michigan: U.S. Geological Survey, Miscellaneous Map Series, GQ-1226.
- Condie, K.C., Bobrow, D.J., and Card, K.D., 1987, Geochemistry of Precambrian Mafic Dykes from the Southern Superior Province of the Canadian Shield, in: Mafic Dyke Swarms, H.C. Halls and W.F. Fahrig editors, Geological Association of Canada Special Paper 34, p. 95-108.
- Gair, J.E. and Thaden, R.E., 1968, Geology of the Marquette and Sands Quadrangles, Marquette County, Michigan: U.S. Geological Survey Prof. Paper 397, 77 pp.
- Gates, T.M. and Hurley, P.M., 1973, Evaluation of Rb-Sr Dating Methods Applied to Matachewan, Abitibi, MacKenzie and Sudbury Dike Swarms in Canada: Canadian Journal of Earth Sciences, v. 10, p. 900-919.
- Kantor, J.A., 1969, Assimilation and Dike Swarms in the Sugarloaf Mountain Area, Marquette County, Michigan: M.S. Thesis, Michigan Technological University, Houghton, Michigan, 83 pp.
- Owens, E.O., 1986, Precambrian Geology and Precious Metal Mineralization of the Fire Center Area, Marquette County, Michigan: M.S. Thesis, Michigan Technological University, Houghton, Michigan, 152 pp.
- Puffet, W.P., 1974, Geology of the Negaunee Quadrangle, Marquette County, Michigan: U.S. Geological Survey, Prof. Paper 788, 53 pp.

Preliminary Paleomagnetic Study of
The Amberg and Athelstane Granites
in Northeastern Wisconsin

Theresa M. Bodus
and
William F. Kean
Department of Geosciences
University of Wisconsin-Milwaukee, WI 53201

The Amberg and Athelstane granites of Marinette County, Wisconsin have compositions which are similar to the Penokean granites of Northern Wisconsin, but the ages tend to overlap with the post Penokean granites of south central Wisconsin. In addition, the grey Amberg granite cross-cuts the pink Athelstane granite and gives an Rb/Sr age of $1650 \pm$ m.y.a.

This study was started to help define the chronology of the igneous intrusives and to determine if there is any similarities between the paleopole positions of these samples and those of the 1760 m.y. old granites and rhyolites of south central Wisconsin. Ten oriented hand samples were collected from the intrusives and analyzed for magnetic stability and magnetic directions. Preliminary results indicate about half the samples were stable enough to provide well clustered magnetic directions. In addition, the magnetic directions for the Amberg and the Athelstane granites are not similar. The magnetic direction of the Amberg granite seem to be associated with the 1650 m.y. overprint whereas the Athelstane pole positions may be associated with either 1760 m.y. or 1450 m.y. It is further suggested that the Amberg and Athelstane granites are not simply single intrusives, but are probably the main components in a large intrusive complex.

**An Unusual Apatite-Rich Nelsonite-, Pyroxenite-, and Hornblendite-Bearing
Intrusion of
Post-Penokean Age, Central Minnesota**

Terrence J. Boerboom, Minnesota Geological Survey,
2642 University Ave., St. Paul, Minnesota 55414

A small pluglike intrusion in central Minnesota contains very apatite-rich rocks ranging from nelsonite (oxide-apatite rock) to pyroxenite, hornblendite, and diorite. As judged from magnetic data, the plug has a diameter of about 2.5 km, and is concentrically zoned. Petrochemical data indicate that the plug is subalkalic to alkalic in composition and is characterized by atypically high values of Fe, Ti, P, and H₂O, but is depleted in K and Si. The distinctive magnetic anomaly (Fig. 1), combined with rock distribution patterns, defines a plug-like geometry and concentrically-zoned intrusion 2.5 km in diameter. It intrudes conglomeratic rocks of Early Proterozoic age, and is located along the trace of the Great Lakes tectonic zone, a major E-NE trending structural boundary in east-central Minnesota. This intrusion forms one of many sharp, small magnetic anomalies in central Minnesota. Regional relationships imply that these plutons are syn- to post-tectonic with regard to the Penokean orogeny. A few scattered outcrops of the pluton exist, and it has been intersected by 12 drill holes totaling 250 m, which were drilled early in the 1900s during iron-ore exploration.

The dominant rock type in outcrop is melanocratic to mesocratic ferrodiorite; the latter contains pegmatitic veins and anorthositic segregations. Hornblendite is gradational into pyroxenite, which together with nelsonite form a significant fraction of the intrusion. Approximately 80% of the core footage is hornblendite/pyroxenite, 10% nelsonite, and 10% diorite. The nelsonite, pyroxenite, and hornblendite are located within the ferrodiorite in a horseshoe-shaped zone, and are seen only in drill core.

The ferrodiorite is medium- to coarse-grained and consists dominantly of andesine (An₄₀₋₅₀), ferropargasitic hornblende, actinolite, apatite, magnetite, ilmenite, augite (Ca₄₃Mg₃₇Fe₂₀) and lesser amounts of albite. Apatite is prominent in the meladiorite, comprising as much as 15% of the modal volume. Layering defined by either cumulus or flow-aligned plagioclase crystals and by centimeter-scale modal variations of feldspar and hornblende is concordant with the edge of the intrusion and dips steeply towards the center.

Hornblendite and pyroxenite are dark green, medium grained, and equigranular. The two rock types are gradational, depending mainly upon the degree to which pyroxene has been replaced by hornblende and actinolite. Dominant minerals in both rock types include primary and secondary ferropargasitic hornblende, augite (Ca₄₉Mg₂₉Fe₂₂), actinolite, Fe-Ti oxides, and apatite. Tabular zoned magmatic hornblende is common, and consists of a red-brown ferropargasitic core rimmed by rhythmic dark green and colorless overgrowths of increasing actinolitic content. Textural evidence shows that cumulus augite was replaced by magmatically related prismatic ferropargasitic hornblende, and both augite and hornblende were subsequently replaced by fibrous actinolite. In extreme cases the rock is composed of a felted mat of actinolite that has obliterated all primary grain boundaries. Modes of oxides range from 10% to 80%, and the latter rocks grade into nelsonite. Very minor amounts of interstitial, magmatic sphene and calcite are present in both hornblendite and nelsonite.

Black and white, strongly magnetic nelsonite contains variable amounts of chlorite, actinolite, hornblende, and pyroxene. Oxides consist of equant magnetite grains, which contain abundant (111) exsolved lamellar ilmenite, as well as grains of late

anhedral ilmenite. Grains of prismatic apatite are a prominent feature of the nelsonite.

This intrusion contains appreciable apatite and therefore it could be a possible source of P. By analogy with other apatite-rich bodies it could also be a source of rare earth elements. Limited analyses of the nelsonite and pyroxenite show up to 13% TiO_2 and 50% Fe_2O_3 ; this implies that the pluton could also be a source of these commodities. Although none of the material now available contains more than 15% apatite or 10% free ilmenite not tied up in magnetite, the existing core (7 cm per 1.5 m) was probably biased toward the iron-rich units. It is almost a certainty that a simple drilling program would intersect intervals of considerable apatite content and/or zones containing economic amounts of recoverable ilmenite. Exploration would be enhanced by the well-constrained size of the pluton and by the fact that it is buried by no more than 30 m of glacial material.

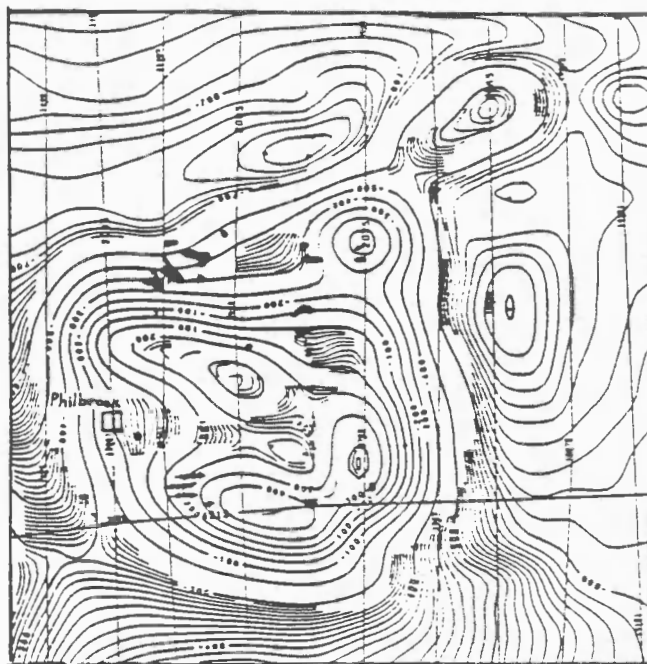


Figure 1. Aeromagnetic map of the Philbrook area (modified from the Minnesota Geological Survey, Legislative Commission on Minnesota Resources, aeromagnetic map of the Motley 7.5 quadrangle.) showing locations of outcrops and drill holes used in this study. Outcrops ●; drill holes ---.

An Introduction to the Geology and Mineral Deposits of the Archean Marquette Greenstone Belt, Michigan

T.J. BORNHORST (Department of Geology and Geological Engineering,
Michigan Technological University, Houghton, Michigan 49931)

The Marquette Greenstone Belt occupies an area of about 125 mi² (325 km²) in northern Marquette County, Michigan. The geology is complex. The belt consists of several thousand feet of subaqueous mafic to silicic flows and pyroclastics and volcanoclastic sediments. It is dominated by tholeiitic basalt, with a scattering of compositions towards rhyolite. These rocks are intruded by gabbro and rhyolite dikes, and by granitoid plutons. The belt includes two peridotite bodies. All rocks are of Archean age. Stratigraphic correlations are complicated by the existence of faults and shear zones. Stratigraphy of the belt will be discussed, with suggestions for improving the current stratigraphic nomenclature.

All of these rocks have been metamorphosed from greenschist to amphibolite facies and subjected to multiple deformation during the Archean. Near vertical dips are quite common. Regionally, the belt is affected by two major Archean shear zones. The Carp River Falls Shear Zone trends E-W and lies along the southern boundary of the belt. It is cut by much less deformed mafic dikes of Archean age (Baxter and Bornhorst, this volume). The full width of the shear zone is unknown because part of it was reactivated during the Penokean orogeny, juxtaposing less deformed Lower Proterozoic sediments against more altered and sheared Archean rocks. The Carp River Falls Shear Zone may be part of the Great Lakes Tectonic Zone of Sims (1980, Geol. Soc. Amer. Special Paper 182, p. 113-124). The second major structural zone, Dead River Basin Shear Zone, trends NW-SE and bisects the belt, with unknown displacement. It too was reactivated during the Penokean orogeny. Stratigraphic correlation across this zone is tenuous.

Of the numerous base and precious metal orebodies and occurrences known in the belt, the Ropes Mine is the most significant. Most of the occurrences are interpreted to be epigenetic, spatially associated with faults and shear zones, and syn- to post-tectonic. Regional structures may be important in localizing mineralization. Precious metal mineralization is accompanied by sulfide minerals, especially pyrite with lesser amounts of pyrrhotite, chalcopyrite, and arsenopyrite, and by non-metallic minerals such as quartz, carbonate, chlorite, and sericite. The present data permits the tentative suggestion that there have been at least two major pulses of mineralization. The potential for discovery of new economic deposits in the Marquette Greenstone Belt is indicated by anomalous geochemical Au values, the occurrence of numerous quartz and carbonate veins, areas of pervasive alteration, areas of relatively abundant faults and shear zones, and the overall geologic setting.

THE ORIGIN AND EXTENT OF THE HARD AND SOFT IRON ORES OF THE MARQUETTE RANGE, MICHIGAN

Burton H. Boyum
Ishpeming, Michigan 49849

ABSTRACT

The Marquette Mineral District is located in the north central part of the Upper Peninsula of Michigan as shown in Figure 1. The principal mineralization is iron with other relatively minor occurrences of gold and of copper. The host rocks are found in the Marquette Range Supergroup of Middle Precambrian age. There are several iron-formation members with the Negaunee Iron-Formation the principal locus of high grade iron ores. Although generally similar to the other iron-formations of the Lake Superior Region, it is the thickest reaching a stratigraphic thickness of over 1,300 meters (3500 feet). It differs also in that it contains a minimum of argillaceous or arenaceous facies.

The "soft" ores are hematite and goethite, soft, friable to earthy or plastic. The "hard" ores are dense to specular hematite and magnetite. There are three distinct structural locations for the ores. The soft ones are found at the base of the Negaunee Iron-Formation, generally in fault structures with intrusive dikes; and on large intrusive sills, also in structures related to faulting. The hard ores are found near the top of the Negaunee Iron-Formation. The Marquette Range is the only one in the Lake Superior Region to have both hard and soft ores.

The regional metamorphism has zones ranging from chlorite in Negaunee and Ishpeming, where the bulk of the soft ore was found, through biotite, garnet, staurolite to sillimanite. Most of the hard ore was found in the higher orders of metamorphism.

From 1846 through 1986 a total of 575,900,119 long tons of iron ore have been produced and shipped from the Marquette Range, including concentrates and pellets from low grade operations. Of the natural, high grade ores 186,607,540 tons were footwall soft ore, 54,092,030 tons were intrusive sill structure soft ore and 60,350,944 tons were hard ore.

The extent of the ores are illustrated by their plan and thickness as related to structural controls. Hypotheses of origin are discussed.

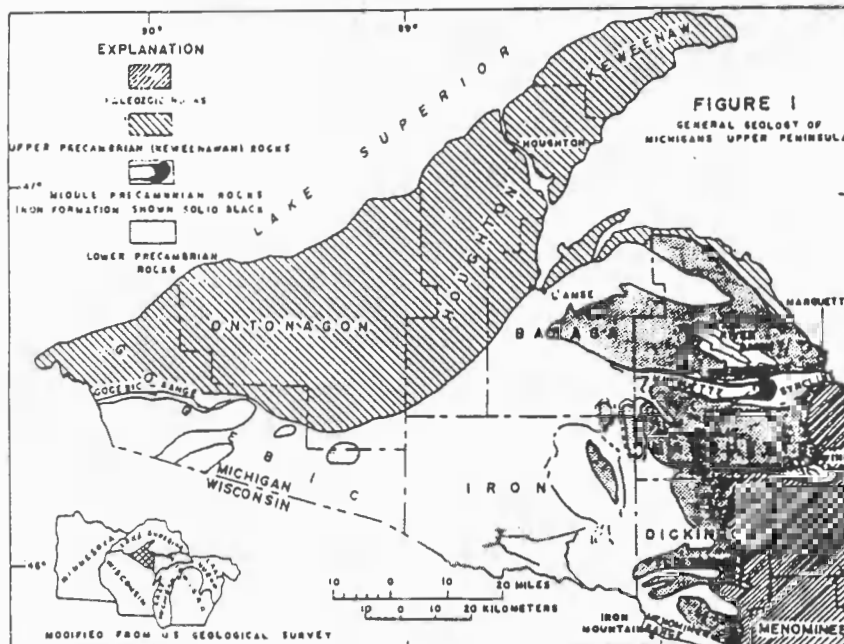


Figure 1 - Generalized geology of the western half of the Upper Peninsula of Michigan

STRATIGRAPHY AND GEOBAROMETRY OF MONZODIORITES FROM THE GIANTS RANGE BATHOLITH, NORTHEASTERN MINNESOTA

Bruce L. Brasaemle, Department of Geology and Geophysics, University of Minnesota, Minneapolis, MN 55455

Mapping in the northeastern part of the Archean Giants Range batholith (in the Bear Island quadrangle), near Ely, Minnesota has revealed a suite of five mappable granitic units ranging in composition from hornblende monzodiorite to granodiorite (Fig. 1). These units are comparable to the Farm Lake facies of the Giants Range batholith proposed by Green (1970) for granitic rocks in the Gabbro Lake quadrangle.

All of the granitoids in the Bear Island quadrangle are generally medium- to coarse-grained, and variably porphyritic with microcline being the most common type of phenocryst. The different granitic units are distinguished on the basis of texture and modal mineralogy, especially modal abundances of quartz, hornblende, and/or biotite. Contacts between the units, where observable, are gradational. Dikes of the quartz monzodiorite (Agqm) cut the hornblende monzodiorite (Aghm), but the stratigraphic relations of Agmd to the other units could not be deciphered in the field. Nevertheless, it is plausible to assume that the units are genetically related. The "mg" values ($Mg/(Mg+Fe)$) of hornblende and/or whole rocks (based on Fe^{++} only) suggest a differentiation sequence of the principal units: Aghm $\rightarrow$ Agmd $\rightarrow$ Agqm (see Table 1).

Pressure determinations based on hornblende stoichiometry (Hammarstrom and Zen, 1986; Hollister and others, 1987) are shown in Fig. 1. Assuming that the stratigraphic and geobarometric deductions are correct, two structural models could account for the observed geologic relations. The observed distribution of these granitic rocks could represent: 1) the faulted record of a composite intrusion (Fig. 2), or 2) a product of asymmetric folding of such an intrusion (Fig. 3). Model 1 seems less plausible because of the lack of field evidence for faults other than the regional northeast trending faults shown in Fig. 1.

References

- Brasaemle, B. L., Southwick D. L., and Sims, P. K., in prep., Bedrock geologic map of Bear Island quadrangle, St. Louis County, Minnesota: Minnesota Geological Survey Miscellaneous Map Series, scale 1:24,000.
- Green, J. C., 1970, Lower Precambrian rocks of the Gabbro Lake quadrangle, northeastern Minnesota: Minnesota Geological Survey Special Publication Series, SP-13, 96p.
- Hammarstrom, J. M., and Zen, E., 1986, Aluminum in hornblende: An empirical igneous geobarometer: *American Mineralogist*, v. 71, p. 1297-1313.
- Hollister, L. S., Grissom, G. C., Peters, E. K., Stowell, H. H., and Sisson, V. B., 1987, Confirmation of the empirical correlation of Al in hornblende with pressure of solidification of calc-alkaline plutons: *American Mineralogist*, v. 72, p. 231-239.

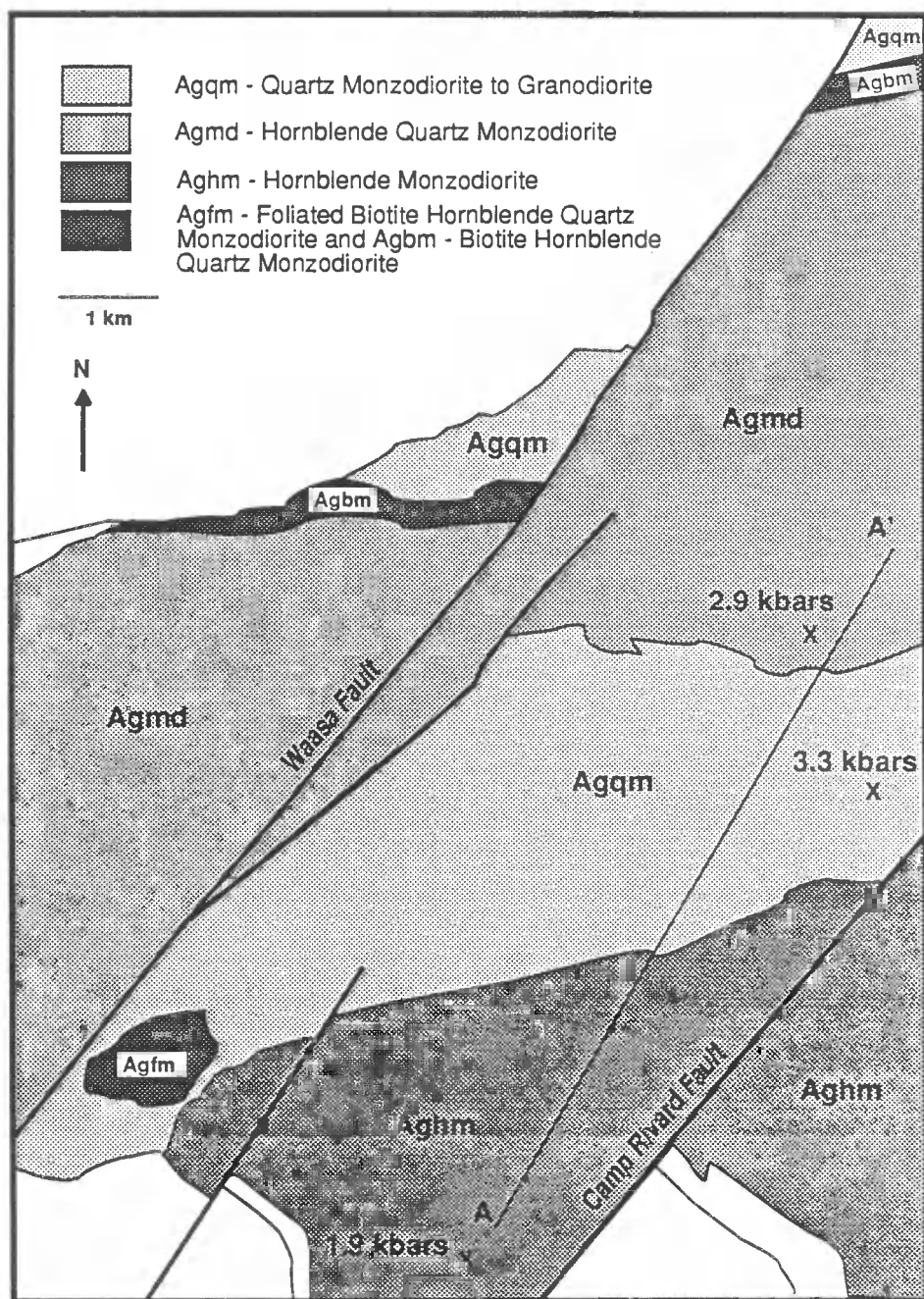


Fig. 1 Schematic map of granitic units of the Giants Range batholith in the Bear Island quadrangle (modified from Brasaemle, and others, in prep.)

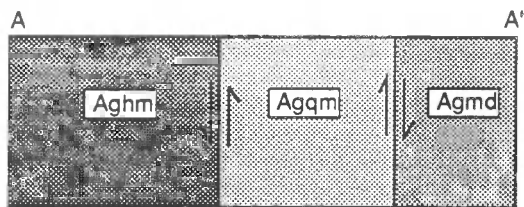


Fig. 2 Faulting of a composite intrusion to account for observed geologic relations of granitic units.

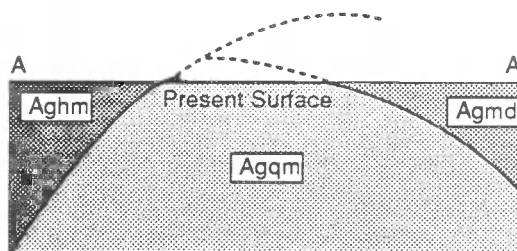


Fig. 3 Asymmetric folding of a composite intrusion to account for observed geologic relations of granitic units.

Table 1. Monzodiorite whole rock and hornblende analyses.

Whole Rock Analyses				Hornblende Analyses							
Unit	Aghm	Agmd	Agqm	Unit	Aghm	Agmd	Agqm	Cations (based on 23 oxygens)			
Sample #	33A	14B	319	Sample #	33A	14B	319	Unit	Aghm	Agmd	Agqm
Oxides (wt %)				Oxides (wt %)				Sample #	33A	14B	319
SiO2	56.3	64.9	71.0	SiO2	48.21	47.53	43.74	Si	7.04	6.97	6.69
Al2O3	17.7	17.5	16.3	Al2O3	6.88	7.56	8.02	Al(iv)	0.93	1.03	1.31
TiO2	0.63	0.37	0.13	TiO2	0.94	0.75	0.77	Al(tot)	1.18	1.31	1.45
Fe2O3	2.57	1.21	0.55	MgO	14.34	13.02	12.18	Al(vi)	0.22	0.28	0.14
FeO	3.32	1.92	0.67	FeO	14.40	16.40	17.94	Ti	0.10	0.08	0.09
MnO	0.10	0.05	0.03	MnO	0.40	0.34	0.60	Mg	3.12	2.85	2.78
MgO	3.38	1.92	0.65	CaO	11.35	11.46	11.06	Fe+2	1.76	1.95	2.30
CaO	4.93	3.90	1.84	Na2O	1.36	1.48	1.35	Mn	0.49	0.42	0.08
Na2O	5.40	6.20	5.90	K2O	0.68	0.81	1.03	Ca	1.77	1.80	1.81
K2O	2.84	2.25	2.73					Na	0.37	0.42	0.40
P2O5	0.50	0.16	0.06					K	0.13	0.15	0.20
Total	97.67	100.60	99.86								
Mg/(Mg+Fe2+)	0.645	0.641	0.635					Mg/	0.640	0.594	0.548
(atomic)								(Mg+Fe)			

A TECTONIC MODEL FOR THE MID-CONTINENTAL RIFT SYSTEM

F. William Cambray
Department of Geological Sciences
Michigan State University
East Lansing, MI 48824-1115

The opening vector of the MRS is restricted to an approximate north-south direction because its continuous nature through almost 180° of arc from Kansas, north to the Lake Superior Region and then south through Michigan, has been established by gravity, magnetic and seismic reflection studies. Motion on such a rift system would be largely extensional in regions at right angles to the opening vector and increasingly transtensional as the angle decreased. This seems to be born out by the greater width of the basin in the east-west trending Lake Superior portion when compared with the narrower geophysical anomalies on the more north-south sections. In addition, the rift fits an asymmetric model such as that of Wernicke (1981, 1985) or Lister et al. (1986) in the Lake Superior region. The south side appears to be the lower plate with the greater thickness and more complex pattern of sediments close to that margin. The lower plate uplift close to the upper plate margin described in the Lister et al. model is represented by the deep level of erosion exposing the Duluth Gabbro and the higher grade metamorphic rocks on the northwest shore of Lake Superior. Finally, the MRS has been involved in a later compressional event. The vector of movement for this phase would also be restricted to an approximately north-south direction in a rigid crust. The thrusting and folding in the Lake Superior region is related to this movement. Elsewhere the motion must have involved various amounts of transpression. The St. Croix Horst and its continuation to the south could be described as a positive flower structure in this setting. The model can be further tested in the field by collecting kinematic data from fault surfaces and finite strain data from fold structures. The detachment fault should be exposed to the north and west of the gabbro.

Variations in Structural Style of the Midcontinent Rift Beneath Lake Superior

W. F. Cannon, USGS, Reston, Virginia
A. G. Green, Geological Survey of Canada, Ottawa, Canada
D. R. Hutchinson, USGS, Woods Hole, Massachusetts
J. C. Behrendt, USGS, Denver, Colorado

Recent deep seismic reflection profiles by the Great Lakes International Multidisciplinary Program on Crustal Evolution (GLIMPCE) not only show details of the deep structure of the Midcontinent Rift beneath Lake Superior but also indicate structural changes along the trend of the rift that suggest changes in the rifting process. These new data, combined with potential field data, support an interpretation of rifting and subsidence of discrete blocks having dimensions of a few tens to a few hundred kilometers. Individual blocks appear to have flexed during subsidence rather than being completely rigid. In some areas, subsidence of as much as 10 km appears to have occurred purely by crustal flexing within an individual block. Boundaries of the blocks, however, are probably faults. On seismic lines, boundaries are shown by abrupt changes in thickness and/or attitude of rift-filled volcanic and sedimentary rocks. In some cases, seismic images of the fault planes were obtained.

In western Lake Superior, the rift appears to be an asymmetric graben deepest (~30 km) on the north, whereas in the central part of the lake, the graben is deepest on the south. A zone of accommodation between these two grabens is inferred along a prominent offset in the gravity pattern extending from just west of Isle Royale to near Ontonagon, Michigan.

The structure beneath eastern Lake Superior is more symmetrical, and an area at least 80 km wide appears to have subsided uniformly about 15 km, with little or no tilting, before undergoing an additional 15 km of more complex subsidence. The Thiel fault, a structure long recognized from potential field data, extending from near Marathon, Ontario, to near Marquette, Michigan, is proposed as an accommodation zone between structures in the eastern and central lake.

The unusual pattern in Bouguer gravity anomalies beneath much of the lake, where trends of linear gravity anomalies end abruptly or show sharp changes in trend, is interpreted to reflect the outlines of discrete blocks of prerift basement. The independent movement of these blocks during rifting controlled the thickness of basalts that filled the rift. Detailed configuration of the rift, therefore, may be inherited from older structures in the Archean and Lower Proterozoic basement that were reactivated as faults during rifting.

COPPER-NICKEL MINERALIZATION OF THE DULUTH COMPLEX,
NORTHEASTERN MINNESOTA: A GRAVITY AND MAGNETIC PERSPECTIVE

Val W. Chandler and Robert J. Ferderer, Minnesota Geological Survey,
2642 University Avenue, St. Paul, Minnesota 55114-1057

It is now generally accepted that interaction between magmas of the Duluth Complex (Middle Proterozoic) and the sulfur-rich Virginia Formation (Early Proterozoic) played a key role in forming the Cu-Ni sulfides near the base of the complex, but many details regarding their evolution remain unknown (Ripley, 1986). Gravity and high-resolution aeromagnetic data are useful in elucidating the structural setting for the Cu-Ni sulfide deposits in the Hoyt Lakes-Kawishiwi area. The sulfide deposits themselves generally lack a direct gravity and magnetic signature, but associated inclusions of wall rock, as well as structures near the base of the complex, can produce strong magnetic signatures especially if any involve the Early Proterozoic Biwabik Iron Formation. For example, contact metamorphosed iron-formation in the Babbitt area produces a prominent, northeast-striking magnetic signature. A spur-like eastward projection of this signature reflects a step-like structure in the basal contact at the MINNAMAX deposit. Detailed magnetic modeling of the MINNAMAX area indicates that the Biwabik Iron Formation thins appreciably across this step-like structure and ultimately pinches out a short distance down dip between the complex and the underlying Archean granite. The fit of the model is improved if more iron-formation is included several kilometers farther down dip along the basal contact.

Several kilometers south of the MINNAMAX deposit, well within the interior of the complex, prominent magnetic anomalies sharply outline an area containing abundant inclusions of hornfelsed wall rock. These anomalies demonstrate that areas of interaction between wall rock magma and are not restricted to the basal contact of the complex.

Many of the sulfide deposits in the Hoyt Lakes-Kawishiwi area lie along northwest-striking lineaments observed in derivative-enhanced gravity and aeromagnetic data. The lineaments cut both the complex and the surrounding wall rocks and are believed to represent late Archean faults that were reactivated during emplacement of the complex. These lineaments support Weiblen and Morey's (1976) idea that northwest-striking faults enhanced sulfide deposition, either by providing conduits for volatiles or by enhancing wall rock interaction along fractures.

Gravity and magnetic modeling of the Hoyt Lakes-Kawishiwi area indicates that the base of the complex dips about 15° to the southeast. The models indicate that in the Hoyt Lakes-Kawishiwi area the Biwabik Iron Formation and presumably the overlying Virginia Formation dip subparallel to the basal contact and may locally occur along its subsurface extension. Under these conditions magma ascending along the basal contact would have a lengthy reaction time with the Virginia Formation, which is consistent with results of sulfur and oxygen isotopic studies (Ripley, 1986). Model studies south of the study area indicate that the base of the complex there dips much more steeply and abruptly truncates the Virginia Formation (Ferderer, 1982). The consequent decrease in reaction surface of the

Virginia Formation might explain the lack of significant Cu-Ni sulfides in the southern part of the Duluth Complex.

Acknowledgment

This study was supported by the Legislative Commission on Minnesota Resources.

References Cited

- Ferderer, R.J., 1982, Gravity and magnetic modeling of the southern half of the Duluth Complex, northeastern Minnesota: Unpublished, M.A. thesis, Indiana University, 99 p.
- Ripley, E.M., 1986, Application of stable isotopic studies to problems of magmatic sulfide ore genesis with special reference to the Duluth Complex, Minnesota, in Friedrich and others, Geology and metallogeny of copper deposits: Berlin, Heidelberg, Springer-Verlag, p. 25-42.
- Weiblen, P.W., and Morey, G.B., 1976, Textural and compositional characteristics of sulfide ores from the basal contact zone of the South Kawishiwi intrusion, Duluth Complex, northeastern Minnesota: in Mining Symposium, 37th Annual, and American Institute of Mining and Metallurgical Engineers, Minnesota Section, 4th Annual Meeting, Duluth, 1976, Proceedings: Minneapolis, University of Minnesota, Continuing Education and Extension, paper 22, 24 p.

Paragenetic Relationships Among Siderite, Magnetite,
Calcite, Quartz, and Sulfides in the Macleod Siderite Mine,
Wawa, Ontario

M. Cohen, J. Mancuso, J. Frizado, D. Stewart
Bowling Green University, Bowling Green, Ohio 43403

E. Berdusco
Algoma Ore Division, Wawa, Ontario POS 1K0

The Macleod Mine is located four kilometers north of Wawa, Ontario and lies within the Helen Iron Range in the Wawa Greenstone Belt of the Superior Province of the Canadian Shield. The mine is an underground siderite mine that began production in 1949 and has continued to the present. It has produced an estimated 80 million tons of ore through 1986.

The siderite-pyrite-banded chert iron formation is conformable between underlying felsic tuffs and overlying intermediate flows and pillow lavas. The iron formation and adjacent volcanics form the south limb of an overturned syncline plunging approximately 35 degrees to the east. The overturned limb strikes east-west and dips approximately 60 degrees to the south. The age of the iron formation has been determined by U-Pb dating of underlying volcanics to be 2750 Ma. before present.

The iron formation consists of a thin, basal banded chert member (1-2m) overlain by the massive siderite (30-100m). The siderite member is overlain by massive pyrite (3-15m) grading to a banded chert member several hundred meters in thickness. The mine itself is located within the massive siderite member.

Mine mapping in the massive siderite and petrographic analyses of selected samples indicate the following paragenetic sequence:

1. Magnetite filling fractures and partially replacing siderite.
2. Calcite filling fractures crossing magnetite and siderite.
3. Multiple episodes of quartz, sulfide, and tourmaline veining.

The origin of magnetite in Precambrian iron formations has long been an unresolved problem. Theories proposed vary from primary sedimentary through diagenetic and metamorphic to exhalative. In the MacLeod Mine the magnetite is definitely secondary because it selectively replaces siderite and fills fractures.

PRECAMBRIAN RED BLUFF GRANITE COMPLEX, WEST TEXAS: COMPARISON
WITH OTHER MID-PROTEROZOIC "RAPAKIVI" GRANITES

Donald M. Davidson, Jr.
Department of Geology
Northern Illinois University,
DeKalb, IL 60115

The Red Bluff Granite Complex is exposed over an area of 20 square km in the Franklin Mountains, near El Paso, Texas. The RBGC intrudes metasedimentary supracrustal units and an ignimbrite cap (Harbour, 1960).

Seven phases have been mapped thus far in this 1 b.y. batholith. Two early microgranite sills are spatially separated 6 km from a three-phase ring complex by a younger tin-bearing biotite granite which cores the complex. A riebeckite granite is the youngest phase, although pegmatites and aplites cut all units.

All phases except the riebeckite granite are medium to coarse-grained with equigranular, porphyritic textures. Several phases display rapakivi texture. Quartz and alkali feldspar constitute 90% of minerals observed. The riebeckite granite typically exhibits an inequigranular, hypidiomorphic texture and contains plagioclase as a major mineral component (up to 38%). Riebeckite crystals show strongly preferred orientations and granulated textures are observed locally. Elsewhere the unit is pegmatitic (Ray, 1982; McCutcheon, 1982).

As with many mid-Proterozoic rapakivi granites, the RBGC is marginally peraluminous ($\text{Al}_2\text{O}_3 > \text{K}_2\text{O} + \text{CaO} + \text{Na}_2\text{O}$), but with peralkaline tendencies. Moreover, the RBGC is enriched in SiO_2 and strongly depleted in Al_2O_3 , MnO , MgO , and CaO compared with other such bodies of similar age (Anderson, 1983) or the "average" granite of Nockolds (1978).

Units of the RBGC show high K, Ba, and REE values suggestive of derivation from a crustal source. Plotted on a Rb/Nb-Y tectonic discrimination diagram (Pearce and others, 1984) data for the RBGC fall in the "within plate" field. However, such a category does not preclude a relationship to subducting lithosphere. If true, this batholith may represent the westernmost manifestation of the Grenville orogeny.

REFERENCES

- Anderson, J.L., 1983, Proterozoic anorogenic granite plutonism of North America: Geological Society of America Memoir 161, p.133-154.
- Harbour, R.L., 1960, Precambrian rocks at North Franklin Mountain, Texas: American Association of Petroleum Geologists Bulletin, v. 44, p.1785-1792.
- McCutcheon, T., 1982, Petrology and geochemistry of the Precambrian Red Bluff Granite Complex, Northern Franklin Mountains, El Paso County, Texas: unpublished MS thesis, University of Texas, El Paso, p.177.
- Nockolds, S.R., and others, 1978, Petrology for Students: Cambridge University Press, 435p.
- Ray, D.R., 1982, Geology of the Precambrian Red Bluff Granite Complex, Fusselman Canyon area, Franklin Mountains, El Paso County, Texas: unpublished MS thesis, University of Texas, El Paso, 295p.
- Pearce, J.A., and others, 1984, Trace element distribution discrimination diagrams for the tectonic interpretation of granitic rocks: Journal of Petrology, v. p.956-983.

GEOPHYSICAL AND PETROLOGICAL CHARACTERISTICS OF THE CLAM LAKE
INTRUSION--A CONSTRAINT ON THE TIME OF KEWEENAWAN BASIN
DEVELOPMENT

C. Patrick Ervin
Dept. of Geology, Northern Illinois Univ.
DeKalb, IL 60115

James F. Olmsted
Center for Earth & Env. Sci., SUNY-Plattsburgh
Plattsburgh, NY 12901

M.G. Mudrey, Jr.
Wis. Geol. & Nat. Hist. Surv., 3817 Mineral Point Rd.
Madison, WI 53506

The Clam Lake gravity and magnetic anomalies are associated with a layered, medium- to coarse-grained, mafic-rich gabbro, probably of Keweenawan age (Mudrey and others, 1982), intruded into an Archean granite gneiss. The intrusion is located a few kilometers south of the Mellen Complex and has been penetrated by two, nearly-coincident boreholes--one vertical and one inclined 65° to NNW.

The northern Wisconsin aeromagnetic data show the intrusion to be marked by a 7000 gamma anomaly with a wavelength of only 5.5 km, indicating a highly magnetic, shallow source. The field configuration suggests the presence of a significant remanent polarization, which has been confirmed by paleomagnetic analysis (Kean and Swingen, 1981). After reduction-to-the-pole, the magnetic anomaly is slightly oval with an east-northeast trending axis and with a narrowed, westward elongation, suggesting possible extension along a fracture. Model analysis yields an average susceptibility contrast of 0.026 cgs units for a source exhibiting surface relief and having a thickness significantly greater than its depth of burial, which is only slightly over 20 m at one point.

The same source configuration, using a density contrast of 0.5 g/cc, also yields a satisfactory fit to the residual Bouguer anomaly calculated from a small gravity survey made over the intrusion.

Cores from both drillholes were sampled for laboratory analysis. Although the holes are only about 152 m apart, susceptibility and density values are significantly different between the two, and both give generally higher values than the geophysical modeling suggests to be representative of the body. The differences are probably reflective of the proximity of the holes to the edge of the intrusion. The most extreme values occur in the hole believed to be closest to the contact.

The variation in composition is due largely to changes in cumulate phases. Oxide poor zones are composed of cumulus plagioclase (An₄₆₋₅₀) and clinopyroxene (Wo₄₁, En₄₇, Fs₀₉, Ac₀₃) with oxides restricted to the postcumulus fraction. In

contrast, the oxide-rich layers include magnetite and ilmenite in the cumulus fraction as well. Strongly oriented plagioclase occurs in both types of layers parallel to their boundaries and at about 30° to the axis of the drill core. This is most obvious and quite striking in the oxide-rich layers. The orientation increases to about 40° in deeper parts of the core, suggesting a flattening, possibly related to the boundary of the intrusion.

Major and selected trace element data were obtained, along with microprobe data of major mineral phases, to help characterize the body. The unit is extremely rich in TiO₂; however, no abnormal concentrations of vanadium or other trace elements were detected.

Banding in the cores suggests that the intrusion has been rotated 10° to 20° from the vertical, while the paleomagnetic data show no evidence of rotation (Kean and Swingen, 1981). This implies that the body was either (a) emplaced in a tipped position or (b) magnetization was acquired after tipping. The mineral chemistry clearly indicates that the magnetite-ilmenite temperature-oxygen fugacity is subsolidus (around 600°C), which is above the hematite and magnetite blocking temperatures. We conclude, therefore, that the NRM was acquired when the intrusion was in a subsolidus stage in its cooling history, and that tipping of the body occurred during or very slightly after emplacement.

This suggests that significant rotation and evolution of the Keweenawan basin occurred in the middle Keweenawan during emplacement of plutonic bodies and during extrusion of the lavas.

REFERENCES CITED

- Kean, W.F., and Swingen, R.A., 1981, Paleomagnetism of a Keweenawan age intrusive near Clam Lake, Wisconsin, *Geophys. Res. Let.*, v. 8, p. 579-582.
- Mudrey, M.G., Jr., Brown, B.A., and Greenburg, J.K., 1982, Bedrock geologic map of Wisconsin, Wisconsin Geological & Natural History Survey, Madison, Wisconsin.

EMPLACEMENT, MINERALOGY, AND INTERNAL EVOLUTION OF A HIGHLY EVOLVED Li-PEGMATITE IN FLORENCE COUNTY, WISCONSIN

Alexander U. Falster, Wm. B. Simmons, Dept. of Geology and Geophysics, University of New Orleans, Lakefront, New Orleans, LA 70148

Recent investigation of several highly evolved granitic pegmatites in Florence County, Wisconsin, have make it possible to determine numerous details of their origin, their paragenesis and their internal evolution.

One large pegmatite in particular was studied in detail. This pegmatite may exceed 300m in maximum dimension, with a thickness of up to 4.5m. The pegmatite invaded the surrounding country rock concordantly, frequently engulfing heavily tourmalinized screens of country rock in the pegmatite and causing tourmalinization in the surrounding country rock as well. The pegmatite strikes $N20^{\circ}W$ to $N35^{\circ}W$ and dips 60° - 65° in a westerly direction. This pegmatite exhibits a striking partitioning of Mn and Fe along its length. The northern end is Mn-enriched and contains tourmaline var. rubellite, lepidolite, spodumene, lithiophilite, fallowite mangano-columbite/tantalite, and rhodizite, besides quartz, microcline, and albite. The southern segment is enriched in both Mn and Fe and lacks lithiophilite and fallowite, containing instead heterosite-purpurite, mangan-alluaudite, and mangan-huhnerkobelite(?). Spodumene occurs abundantly in the core zones in crystals several times larger than those from the northern segment. Rubellite does not occur in this section but Fe-rich blue-black tourmaline is found in its place.

The tourmaline in both segments occur in large quantity in the outer wall and contact zone, as well as in the inner intermediate zone. A lack of tourmaline in most of the other zones is conspicuous. All phosphates appear with tourmaline in the inner intermediate zone and the core zone. They are absent in the other units.

From country rock distortion it appears that the intruding pegmatitic melt invaded from a south-easterly direction. The most likely source of this and neighboring pegmatites is the Hoskin Lake granite, a Precambrian intrusive of an age of 1,650 million years.

The following list of minerals has been identified to date (EDS, petrographically and by wet chemistry):

Microcline-perthite is the most abundant mineral phase in the pegmatite. It forms blocky grains up to 15 cm across. The color ranges from grayish white in the northern segment to reddish in the southern section.

Albite, var. cleavelandite, evidently with low anorthite content, is widespread and also forms late stage metasomatic units. The color ranges from a bluish gray to white to red brown.

Quartz, of a distinctly gray (and not smoky) color is less abundant than the feldspars. Masses up to several tens of centimeters occur occasionally.

Tourmaline, variety, elbaite (rubellite) occurs abundantly in some of the zones. Deep-blue tourmaline appears to be an elbaite variety.

Spodumene occurs strictly in the core zones. Crystals up to 30 cm have been recovered from the core zones in the southern segment.

Lepidolite is abundant throughout the pegmatite and forms patches and stringers of purple to pinkish-lilac or rarely yellowish flakes (commonly around 1-2mm in diameter) and masses and occasionally some coarse books up to 1.5cm in diameter.

Polythionite has been identified from near the spodumene core where it is found in masses resembling topaz crystals in outline, thus possibly indicating complete alteration of earlier existing topaz. The size of these lumps ranged from 1cm to 6cm, the color is a greenish yellow.

Lithian muscovite has been tentatively identified from a patch in the intermediate zone where it occurs as bright golden-yellow books up to 5mm across.

Apatite occurs throughout the pegmatite with the bulk near the contact. The color is deep blue, the size up to 5mm in maximum dimension. Apatite occurs also as the white core in lithiophilite nodules near the spodumene core. It is rimmed by lithiophilite and finally by fillowite.

Lithiophilite occurs in the intermediate and core zones of the northern segment. The size of the nodules reaches a maximum of 2cm, and generally has a tan to salmon-pink color, in some cases rimmed by black Mn-oxides.

Fillowite occurs as a light tan rim over lithiophilite nodules.

Heterosite-purpurite of the Fe-richer variety was found only at the southern segment as nodules up to 3cm and of purplish-brown color, rimmed by a so far unidentified white mineral and be an outer layer of light blue tourmaline.

Mangan-alluaudite also was only found at the southern segment. It formed olive-brown nodules up to 2cm in diameter. Mangan-huhnerkobelite occurs with mangan-alluaudite as brownish masses up to 1cm in diameter. This is the first reported occurrence for this Mn-rich variety.

Mangan-huhnerkobelite occurs with mangan-alluaudite as brownish masses up to 1cm in diameter. This is the first reported occurrence for this Mn-rich variety.

Mangano-columbite and mangano-tantalite both occur throughout the pegmatite in small amounts in crystals of reddish-black color, up to 2mm in maximum dimension. It is remarkable that both occurred only mm apart in the same sample.

Rhodizite is probably the most remarkable mineral from the pegmatite. It was found as glassy, tan colored grains up to 4mm near the contact of the intermediate and wall zones. Only 2 other localities produced rhodizite: the first is near Swerdlowskz, in the Ural Mountains., USSR, and the second is near Mania, Madagascar.

The internal evolution is believed to have taken the following path: The pegmatitic magma, highly enriched in volatiles, Li, Rb, Cs, B invaded the country rock along bedding planes and planes of weakness. Some partial melting of the country rock may also have occurred, liberating the alkalis of low melting point and possibly B. A thin contact zone up to a few mm formed first, immediately followed by a thick wall zone up to 20 cm. Possibly at this time an interfering influence, either a fluid phase contributed by the country rock, or a pH/Eh differential, caused profuse crystallization of tourmaline. NAA data suggest that the rubellite may indeed have formed relatively early, despite its high Mn/Fe ratio, it is very low in Rb and Cs. These elements occur abundantly in the deep blue tourmaline, indicating a higher degree of differentiation. As the intermediate zones began forming, a magma fluxed by lithium tetraborate may have prevented precipitation of tourmaline and phosphates (due to lack of aqueous fluid). Once the inner intermediate zone began to form, free aqueous fluid began to exsolve, resulting in destabilizing of the tetraborate flux, and in crystallization of large amounts of tourmaline and phosphates. The fluids enriched in Li eventually gave rise to the spodumene core and to replacement units of lepidolite and albite throughout the pegmatite. Finally, escaping fluids, rich in B, created a tourmalized halo in the surrounding country rock.

To date, no evidence of miarolitic cavities in the pegmatite has been found.

Paleomagnetism of Keweenawan Age Basalts From
The Taylor Falls-St. Croix Falls Area of
Wisconsin and Minnesota

John Feeney
and
William F. Kean

Department of Geosciences
University of Wisconsin-Milwaukee
Milwaukee, WI 53201

Ten oriented hand samples from the St. Croix Falls area were measured for magnetic characteristics. A.F. demagnetization and remanence acquisition studies indicate that the remanence is carried by magnetite. Most samples show a single component of magnetization. The paleopole directions are predominately reversed with latitudes ranging from $S40^{\circ}$ to $N10^{\circ}$. The basalts are probably middle Keweenawan in age, based on known reversal patterns for Keweenawan time.

APPLICATION OF WERNER DECONVOLUTION TO THE PENOKEAN FOLD-AND-THRUST BELT, EAST-CENTRAL MINNESOTA

R.J. FERDERER (Department of Geology and Geophysics, University of Minnesota, Minneapolis, MN 55455; and Minnesota Geological Survey, 2642 University Ave., St. Paul, MN 55114)

The geology of the Penokean orogen in east-central Minnesota has recently been reinterpreted by Southwick and others (1988). These authors have divided the orogen into several tectonic elements, including a fold-and-thrust belt and the main bowl of the Animikie basin. The fold-and-thrust belt has been further divided into three zones which are bounded by major structural discontinuities. The discontinuities are defined by changes in metamorphic grade, stratigraphy, and structural style.

Werner deconvolution has proven to be a useful tool for defining structures associated with the Penokean fold-and-thrust belt. This inverse magnetic modeling technique yields position, depth, susceptibility contrast (k) or thickness, and dip estimates for anomaly sources that can be approximated by thin sheets or planar interfaces. Results presented here were obtained within two areas that lie along two of the above-mentioned structural discontinuities, and provide new information on their nature.

One area studied straddles the Malmo structural discontinuity, a southward-dipping thrust zone that separates the internal and medial zones of the fold-and-thrust belt. The presence of this feature is strongly supported by a magnetotelluric modeling study (Wunderman and Young, 1987). Consistent intermediate to steeply southward dipping thin sheet solutions were obtained along the mapped location of the discontinuity in this area (Fig. 1). Depth estimates have an average value of 95 m, and k estimates (calculated for a sheet thickness of 50 m) have an average value of 0.0230 cgs.

The existence of consistent thin sheet solutions over a strike length of at least 40 km implies that the anomaly source is related to the discontinuity, and may represent the fault zone itself. Pyrrhotite-rich graphitic phyllite are common throughout the fold-and-thrust belt and one of these units may have acted as a plane of slippage for the thrust. Alternatively, a layer of magnetite and/or pyrrhotite may have formed in the fault zone, associated with metamorphic processes during faulting, or after deformation. It is also conceivable that the thin sheet solutions represent a magnetic layer oriented subparallel to the fault zone, within the Denham Formation. The presence of a northwest-trending, left-lateral strike-slip fault is also indicated (Fig. 1 b)).

A second area of study lies on the boundary between the fold-and-thrust belt and the main bowl of the Animikie basin. A major north-directed thrust is mapped in this area, as well as an unconformity between rocks of the two tectonic elements mentioned above. Holst (1984) defined a boundary between areas affected by one and by two major phases of folding, approximately 55 km east of this area. The boundary was interpreted to be the outermost limit of the hinge of a major north-directed, isoclinal, recumbent fold that is probably a thrust nappe. Southwick and others (1988) extended this boundary, based on sparse drilling data, to the northeastern edge of the area considered here.

Interface solutions were obtained north of the mapped thrust fault, and have orientations which are consistent with it. Thin sheet solutions were obtained over a distance of greater than 15 km along strike, north of the fault and south of the westward extension of Holst's boundary. Forward modeling was performed using both interface and thin sheet solutions to establish which source type is more appropriate for the anomaly in question. The thin sheet solutions are favored based on similarity between calculated and observed anomalies. The thin sheet solutions dip approximately 65° N and are associated with average depth and k estimates of 300 m and 0.0100 cgs, respectively.

Because of the proximity of the thin sheet solutions to the mapped location of Holst's boundary, it is proposed that the sheet may correspond to a unit, possibly a lean iron-formation, located within the nappe hinge so that northward dips would be expected. The large depth estimates may represent an unconformity separating rocks of the nappe front from overlying sediments that were derived from the stacked thrust pile to the south. It is also possible that the upper portion of the nappe front has been faulted out, possibly by the thrust mapped in this area.

For both of the areas considered, the absence of interface solutions associated with thrust faults may be explained by a low susceptibility contrast between the footwall and hanging wall. Except for iron-formation, most supracrustal rocks in the Penokean orogen in east-central Minnesota are weakly magnetic. Therefore, strong susceptibility contrasts across low-angle faults in these rocks are not likely.

Acknowledgments

This research was funded by the Legislative Commission on Minnesota Resources.

References Cited

- Holst, T.B., 1984, Evidence for nappe development during the early Proterozoic Penokean orogeny, Minnesota: *Geology*, v. 12, p. 135-138.
- Southwick, D.L., Morey, G.B. and McSwiggen, P.L., 1988, Geologic map (scale 1:250,000) of the Penokean orogen, east-central Minnesota, and accompanying text: Minnesota Geological Survey Report of Investigations 37 (in press).
- Wunderman, R.L., and Young, C.T., 1987, Evidence for widespread basement decollement structures and related crustal asymmetry associated with the western limb of the Midcontinent Rift (abs.): Institute on Lake Superior Geology, *Proceedings and Abstracts*, v. 33, pt. 1, p. 85-86.

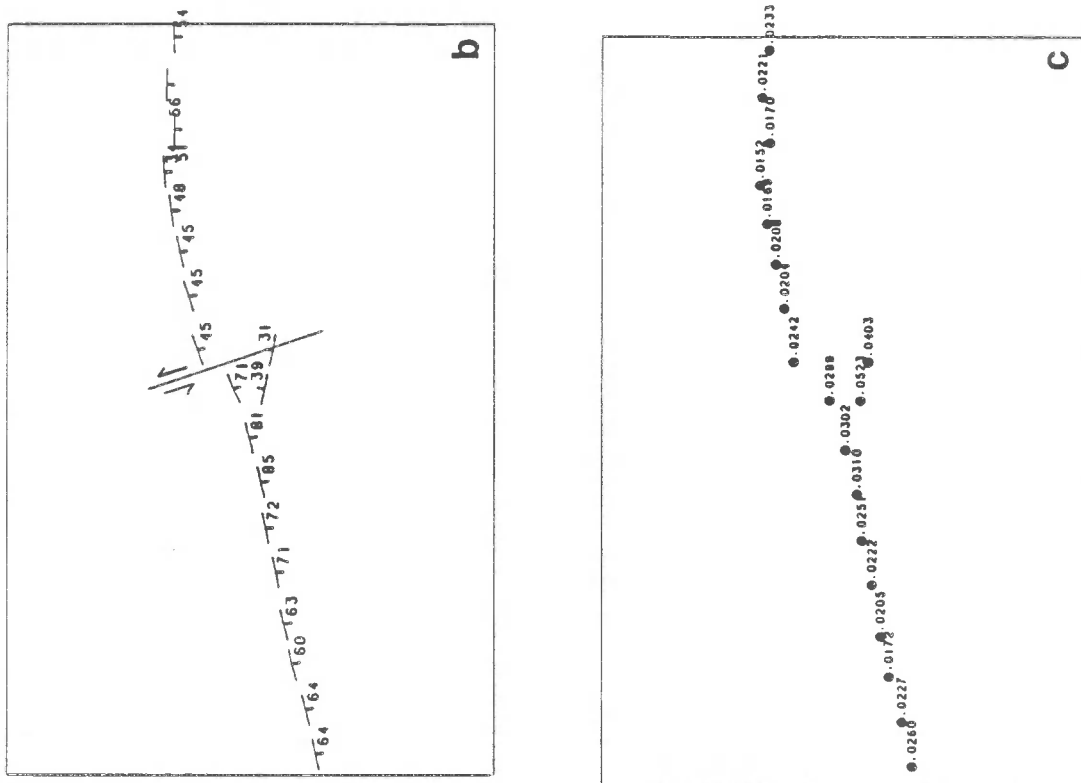


Fig. 1. Werner deconvolution thin sheet; a) depth, b) dip, and c) susceptibility contrast solutions, all obtained along the Malmö structural discontinuity. Depth estimates are in meters and susceptibility estimates are in cgs units.

An investigation into the chemical processes causing the formation of unakite in the Waupaca adamellite of Wisconsin

JODY FRONK and Dion C. Stewart (Department of Geology,
Bowling Green State University, Bowling Green, OH 43403)

Unakite, an epidote-chlorite-rich red granite, is locally developed in the Waupaca adamellite, which is the southern most pluton in the Wolf River batholith of northern Wisconsin. In the Johnson Quarry near the city of Waupaca the unakite occurs in narrow (20 centimeter) linear zones. Forty samples were collected at regular one-meter intervals on two traverses running perpendicular to these zones. Detailed mapping of the quarry was used to establish the orientation of the zones and the location of each sample relative to the unakite zone. Both modal and chemical analyses were conducted on the rocks and their constituent minerals from both traverses.

Results show that unakite occurrence is spatially related to the presence of fracture joints. Three distinct zones are developed in the field in a symmetrical pattern around the fracture joints. Each zone can be characterized by its mineral alterations and either the formation and/or disappearance of specific minerals. The outer most zone is represented by relatively unaltered adamellite, having a strongly developed rapakivi texture and a mode of 17% quartz, 11% biotite, 62% perthitic microcline, 6% plagioclase ($Ab = 93$), and 4% accessories predominately apatite, sphene, opaques and zircon. The first zone of alteration is recognized by the appearance of chlorite and the progressive disappearance of biotite. The second zone is recognized by the appearance of epidote in the groundmass, and a decrease in the amount of microcline, which becomes progressively more red in hand specimen. The central zone, in the fracture lineament, is recognized by a large increase in epidote including the conversion of the rapakivi rims to epidote, a slight increase in plagioclase ($Ab = 99+$), a large decrease in microcline, and the conversion of perthite to antiperthite (bulk mineral $Ab=63$, $Or=36$, $An=1$).

Mass balance calculations using modal abundances, mineral chemistry, and bulk rock chemistry (both major oxides and trace elements) show that the "unakitization" process is accomplished by both redistribution of ions among the rock-forming minerals of the adamellite and the addition and/or subtraction of ions to/from the rock by a hydrothermal fluid. Calcium is redistributed from plagioclase to epidote, and is added to the rock by the fluid. Magnesium and iron are redistributed from biotite to chlorite. Aluminium is redistributed from microcline and plagioclase to chlorite and epidote. Sodium is partially redistributed from perthite and plagioclase to antiperthite and albite. Potassium is partially redistributed from biotite and microcline to antiperthite, but is largely removed from the system by the fluid. These types of chemical alteration are broadly synonymous with the characteristics of "propylitic alteration".

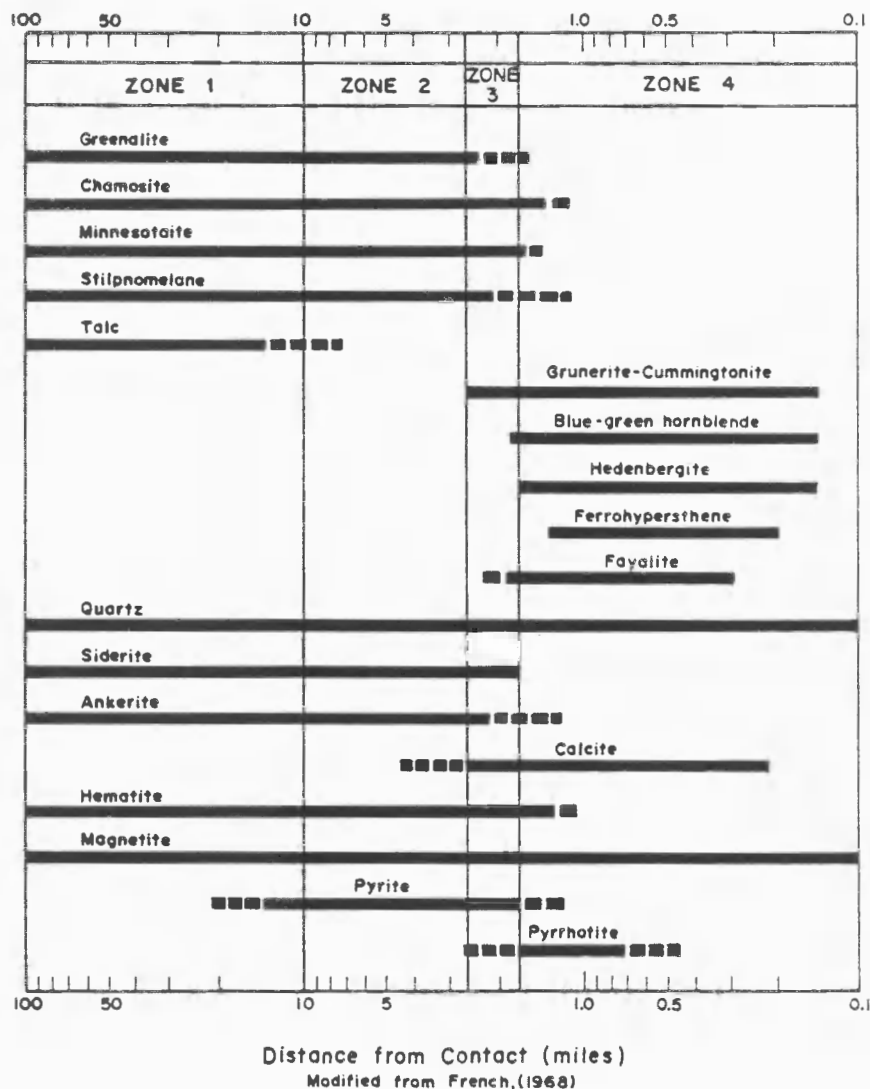
Genesis and Metamorphism of Magnetite in Biwabik Iron-Formation, Mesabi District, Minnesota

by Tsu-Ming Han
The Cleveland-Cliffs Iron Company

Abstract

The Biwabik iron-formation in the Mesabi District extends east-northeast for about 120 miles. The eastern end has been subjected to a progressive contact metamorphism by the intrusion of the Duluth Gabbro Complex. Four metamorphic zones have been established by French (1968) within the iron-formation along the strike toward the contact of the complex. These zones are unaltered (Zone 1), transitional (Zone 2), moderately metamorphosed (Zone 3), and highly metamorphosed (Zone 4).

The following diagram shows the mineralogy of the Biwabik iron-formation in different metamorphic zones as a function of distance from the Duluth Gabbro contact.



This study deals with the genesis of magnetite in the iron-formation, based on its internal microstructures, and the effect of the progressive metamorphism on the internal microstructures of the magnetite in the respective metamorphic zones.

Polished sections prepared from the magnetite-rich specimens of the iron-formation were microscopically examined and reexamined, before and after an induced oxidation. The oxidation was done by heating the polished sections in a stagnant air furnace at about 300°C for three to four days. This oxidation process is rather selective and takes place along either or both the octahedral planes or the preexisting structural weaknesses of the magnetite, depending on the degree of metamorphism.

The magnetite studied was free from martitization, except for traces of hematite inclusions in some of it. This magnetite occurs as granules, laminae, and single or coalesced octahedra in all the metamorphic zones classified. However, the induced oxidation results show the magnetite coexisting with layered type silicates oxidizes along the preexisting structural weaknesses, whereas the magnetite associated with chain type silicates oxidizes mostly along its octahedral planes.

In the unaltered and transitional zones, the hematite generated by the induced oxidation of magnetite outlines the size, morphology and microstructures of the preexisting inclusions within the magnetite. These inclusions have been interpreted as "preexisting hematite" (Han 1987 and 1986). The existing hematite inclusions observed in the magnetite before the induced oxidation are actually unreplaced portions of the preexisting hematite. These preexisting hematite inclusions vary widely in apparent morphology. They may be platy, bladed, hexagonal, rhombohedral, colloform, wedge-shaped, and lath-shaped or in other irregular forms. They exhibit various types of microstructures, such as vuggy, microgeodic, botryoidal, etc.

In the moderately metamorphosed zone, the induced oxidation takes place principally along the cleavage planes of the magnetite. However, the outlines of the preexisting hematite inclusions and their arrangements are still traceable in most of the specimens.

The magnetite from the highly metamorphosed zone oxidizes almost exclusively along the octahedral planes. The internal microstructures created by the preexisting hematite has been almost completely obliterated.

Genetically, it is believed that the preexisting hematite functioned as the principal nuclei responsible for the development of much of the magnetite in the Biwabik iron-formation. The existing magnetite was largely developed by the replacement and overgrowth that occurred concurrently at the interface between the hematite nucleus and its gangue host. The development varies in magnitude from very limited to rather extensive, as indicated by the differences in size and morphology between the existing magnetite and its nucleus. In general, the size, orientation and outlines of the existing magnetite laminae, granules, and coalesced octahedra are dictated by the corresponding features of the preexisting hematite. This clearly demonstrates that the magnetite is not a primary mineral and may also suggest that the so-called carbonate facies and

silicate facies either originally contained hematite or were oxide facies before the postdepositional changes - magnetitization, carbonatization, and silication.

The magnetite developed by the replacement of, and overgrowth on, hematite nuclei suggests that the centripetal ionic diffusion of Fe^{++} was apparently the key magnetite-forming process. Iron was probably initially deposited as a ferric oxide gel associated with siliceous mud. This gel could have dehydrated to colloform layers and granules or could have crystallized to hematite crystals with different microstructures. The gel could also have reacted with carbon to produce Fe^{++} which served as a principal source for the magnetite development. The magnitude of magnetite enrichment was, of course, determined by the Fe^{++} supply which, in turn, was controlled by the availability of oxygen, carbon, and ferric oxide gel. Magnetite development by centripetal diffusion probably occurred during late diagenesis or in the early stages of regional metamorphism.

References

- French, B.M. 1986 Progressive Contact Metamorphism of the Biwabik Iron-Formation, Mesabi Range, Minnesota. Minnesota Geological Survey Bull. 45.
- Han, T.M. 1978 Microstructures of Magnetite as Guides to Its Origin in Some Precambrian Iron-Formations. Fortschritte der Mineralogie, Vol. 56, p. 105-142.
- Han, T.M. (in press) Origin of Magnetite in Precambrian Iron-Formations of Low Metamorphic Grade. Abstr. Terra Cognita, The Journal of the European Union of Geosciences, No. 3, Vol. 6, 1986, p. 563.

SCIENTIFIC DRILLING INTO THE MIDCONTINENT RIFT SYSTEM

William J. Hinze⁽¹⁾ and William C. Kelly⁽²⁾

Approximately 100 geoscientists recently convened in Duluth, Minnesota at a workshop entitled "Scientific Drilling of the Midcontinent Rift System" for the purpose of defining the generic and specific scientific objectives of drilling into the Midcontinent Rift System and to recommend and prioritize drilling sites. This workshop was sponsored by Deep Observation and Sampling of the Earth's Continental Crust, Inc., the Department of Energy and several state surveys interested in the MRC. The Midcontinent Rift (MCR), an 1100 Ma old paleo-rift system extending for more than 2000 km across the midcontinent region, offers excellent opportunities for studying continental rifting processes as well as problems dealing with the evolution of continents. The MCR is unique among rifts because it contains as much as 30 km of rift-related volcanic and sedimentary rocks and several crustal provinces having a range in age of about 2 Ga were cut by the crustal disruption.

Our direct knowledge of the MCR is largely limited to evidence obtained from restricted outcrops in the Lake Superior region and cuttings obtained from widely distributed drill holes where the rift is covered by Phanerozoic sedimentary rocks of the craton. However, geophysical studies and drilling of the overlying Phanerozoic strata have pinpointed many areas along the length of the rift where holes less

(1) Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, IN 47907

(2) Department of Geological Sciences, 1006 C.C. Little Building, University of Michigan, Ann Arbor, MI 48109-1063

than 5-km in depth can be drilled to adequately sample the Proterozoic rocks and investigate their stratigraphic and structural relationships. These relationships and the sampled rocks can be used to study the two primary scientific objectives of drilling into the MCR:

- 1) To investigate the physical and chemical processes involved in the origin and evolution of continental rifts, specifically the MCR; and

- 2) To investigate crust and mantle interaction during the continental rifting process; specifically to identify the mantle reservoirs in the continental lithosphere and the asthenosphere that have acted as sources for rift basalts and presumably reflect the differing ages of the crust and the related mantle.

These two primary themes are particularly attractive for the following reasons. First, they are focused on major geologic problems having broad generic implications, which can be applied to the study of other intraplate rifts. Second, they can be addressed only with fresh samples obtained by drilling; existing outcrops and drill hole samples are inadequate. Third, the drilling program can be staged such that initially, significant progress can be made with several relatively low-cost shallow to intermediate depth holes, the results of which will serve to aid in siting and prioritizing possible deeper holes. Fourth, drilling to achieve the purposes of the primary themes will provide a basic framework into which other studies, such as sedimentology, geophysics, metamorphic geology, fluid chemistry and movement, etc. can be integrated. In fact, the vast majority of the "secondary science" objectives are really essential ingredients that support the primary themes. Fifth, we anticipate that the drilling environment of the MCR will be as benign as one can expect to encounter. Finally, and most significantly, the two primary objectives can, for the most part, be achieved with core samples from the same drill holes.

We propose as a first stage of the MCR drilling program two 3.5- to 4.5-km-deep drill holes, the first in southern Minnesota and the second in northern Kansas. Because of our current knowledge, the drilling program could be initiated in the near future with minimum pre-drilling studies. In addition, we recommend that site selection studies begin in the eastern Northern Peninsula of Michigan, for the purpose of locating drill sites to sample the 20-km-thick tholeiitic basalt section in eastern Lake Superior.

ANIMIKIE GROUP: A PENOKEAN FOREDEEP?

Paul F. Hoffman

Geological Survey of Canada, 312-588 Booth St., Ottawa, Ontario K1A 0E4

Foredeeps (foreland basins) are linear asymmetric basins that migrate in front of, and become incorporated within, foreland thrust-fold belts (Fig. 1). They develop as a flexural response to loading of the continental lithosphere by thrust sheets. Many foredeeps evolve from oceanic trenches when rifted continental margins are drawn into subduction zones (Fig. 2), but they may also result from intracontinental thrusting. Taiwan Strait, the Persian-Arabian Gulf, and the Ganges River basin are examples of active foredeeps in progressive stages of development.

Active foredeeps are bounded in front by flexural forebulges and behind by prograding thrust-fold belts (Fig. 3). Foredeep migration causes diachronous deposition of lithofacies, recognized by the following diagnostic stratigraphic sequence (Fig. 4): (1) pre-foredeep deposits (e.g. passive-margin shelf sediments); (2) short-lived erosional disconformity caused by the migrating forebulge; (3) transgressive outer-ramp (strandline to foreslope) lithofacies; (4) axial turbidites, which may shoal upward to fluvial sediments that are commonly eroded away during immediately subsequent thrust-fold deformation. Foredeep outer-ramps are commonly broken by normal faults, possibly caused by lithospheric bending stresses. The outer-ramp lithofacies are typically chemical, starved of terrigenous sediment, and the axial turbidites are commonly derived along strike from areas of more advanced orogeny (e.g. foreland promontories). However, terrigenous sediments in some foredeeps may be derived directly from the foreland (e.g. Nile cone of the eastern Mediterranean).

The Animikie Group (Marquette Range Supergroup) is one of several possible foredeep sequences of Early Proterozoic age identified in the Canadian shield (Hoffman, 1987). It was deposited on downflexed Archean crust between the Penokean thrust-fold belt to the south, related to accretion of the Early Proterozoic island-arc terrane of central Wisconsin, and the Archean foreland to the north. Accordingly, the pre-foredeep deposits are the Milles Lacs and/or Chocoy group, outer-ramp sediments are represented by the Menominee Group, and the axial deposits by the Baraga Group. As with other Early Proterozoic foredeeps in Canada, the Animikie Group is characterized by outer-ramp iron-formation and axial tholeiitic volcanism.

Traditionally, the Animikie Group has been interpreted as an evolving passive-margin prism. Testable predictions of the foredeep model for the Animikie Group are: (1) the age of Animikie Group deposition (U-Pb dating of flows or tuffs) should be close to that of the Penokean orogeny (ca. 1.85 Ga), and (2) the Animikie Group turbidites may be derived from the Early Proterozoic arc terrain (U-Pb dating of detrital zircons or Nd-Sm model age of terrigenous sediment). However, an Archean source terrain is not excluded in the foredeep model. Preliminary Nd-Sm data point to an Early Proterozoic source for the Animikie Group turbidites (Barovich et al., 1987, 1988).

References

- Barovich, K.M., Patchett, P.J., and Peterman, Z., 1987, Origin of 1.9-1.7 Ga Penokean continental crust of the Lake Superior region: *Eos*, v.68, p.1547.
Barovich, K.M., Patchett, P.J., Peterman, Z.E., and Sims, P.K., 1988, Nd isotopes and the origin of 1.9-1.7 Ga Penokean continental crust of the Lake Superior region: *Geological Society of America Bulletin*, in review.
Hoffman, P.F., 1987, Early Proterozoic foredeeps, foredeep magmatism, and Superior-type iron-formations of the Canadian shield, in *Proterozoic Lithospheric Evolution*: Kröner, A., ed., American Geophysical Union, Geodynamics Series, v.17, p.85-98.

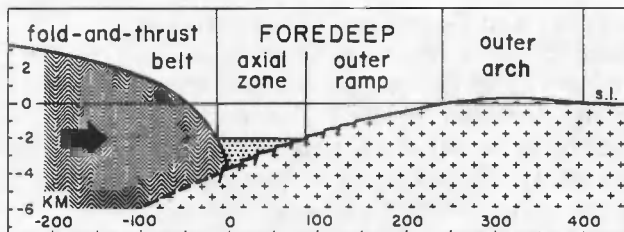


Fig. 1. Tectonic elements associated with foredeeps and nomenclature used in this paper. Note the step-like normal faults forming on the outer ramp. The geometric form of the fold-and-thrust belt is strictly schematic.

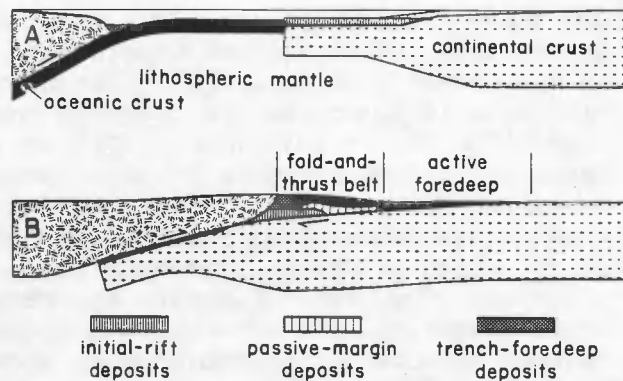


Fig. 2. Evolution of an oceanic trench (A) into a foredeep (B) by attempted subduction of a rifted continental margin.

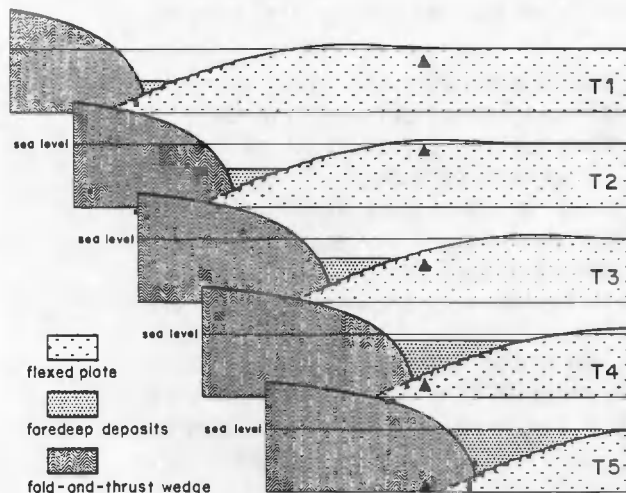


Fig. 3. Foredeep migration causes the site marked by a black triangle to experience uplift and erosion at time T2, deposition of outer-ramp sediment at T3, deposition of axial-zone sediment at T4, and incorporation into the actively deforming allochthonous wedge at T5. Note the progressive sedimentary infilling of the foredeep with time, a diachronous process also in a direction parallel to the foredeep axis.

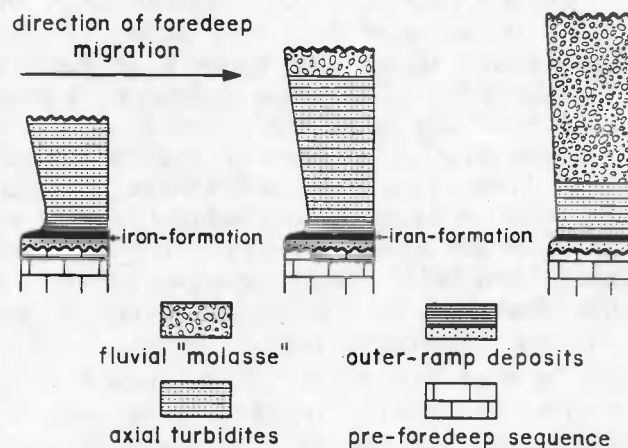


Fig. 4. Typical foredeep stratigraphic sequences. Middle column corresponds to the site of the black triangle in Figure 3. Paleocurrent directions are mainly axial.

UNITED PLATES OF AMERICA: ORIGIN AND EARLY EVOLUTION OF LAURENTIA (2.0 TO 1.0 Ga)

Paul F. Hoffman

Geological Survey of Canada, 312-588 Booth St., Ottawa, Ont. K1A 0E4

The stable Precambrian lithosphere of North America and Greenland (Laurentia) is an aggregate of former microcontinents, welded by a system of 2.0 - 1.8 Ga collision zones (Hoffman, 1988). The microcontinents, clustered in the northern two-thirds of Laurentia, are composed mainly of Archean crust. The collision zones (Fig. 1) are asymmetric: their forelands have shelf-foredeep prisms of relatively low metamorphic grade, deformed by early thin-skinned thrusting and subsequent thick-skinned folding; their hinterlands have linear calc-alkaline and crustal-anatectic magmatic zones, and systems of oblique- and strike-slip shear zones related to oblique subduction and/or post-collisional indentation-extrusion tectonics. The inferred sutures are commonly cryptic, but the Trans-Hudson orogen preserves a 400-km-wide internal zone in Manitoba and Saskatchewan that contains belts of former oceanic island arcs. In northern Quebec, the foreland of the same collision zone preserves a 400x80-km klippe in which a continental-margin rift assemblage is overthrust by transitional oceanic crust, overthrust in turn by an imbricated ophiolite, complete with "sheeted dikes" and mafic-ultramafic cumulates (St-Onge et al., 1988). The location of the exposed Precambrian shield, as opposed to the covered Precambrian platform, is apparently controlled by the distribution of Archean crust, perhaps reflecting its greater buoyancy due to a depleted mantle lithosphere.

Juvenile Proterozoic crust, composed of former island arcs and other oceanic crustal relics, was accreted to the assembled microcontinents prior to 1.6 Ga and during the 1.25-1.0 Ga Grenville orogeny. In western Laurentia, crust of ca 2.2 Ga age was accreted beginning about 1.9 Ga in Wopmay orogen (S.A. Bowring, unpublished data) and appears to be widespread in the parautochthonous(?) Cordillera from California to Alaska. In southeastern and southern Laurentia, belts of 1.9-1.8 Ga crust were accreted in the Penokean and Makkovik-Ketilidian orogens, 1.8-1.7 Ga crust in the Yavapai-Central Plains orogen, and 1.7-1.6 Ga crust in the Labrador and Mazatzal orogens (Hoffman, 1988). These belts extend for 5000 km along strike (including Baltic equivalents) and total 1200 km in width south of the Wyoming province (Fig. 1). Archean crust is rare to absent (Patchett and Arndt, 1986). Beginning about 1.7 Ga, a possible sea-level highstand resulted in the deposition of clastic sediments in widely distributed cratonic basins (eg. Baraboo, Athabasca, Thelon, Hornby).

From at least 1.5 to 1.3 Ga, epizonal syenogranite batholiths and layered gabbro and/or anorthosite massifs were emplaced across much of southern and southeastern Laurentia. In many areas, the Middle Proterozoic "anorogenic" magmatism lacks associated rift faulting, thick alluvial sedimentation, and syn-rift (isostatic) and post-rift (thermal) subsidence normally expected as consequences of lithospheric stretching. Rather than attributing the magmatism to extensional tectonism, it is suggested that the then young Laurentia sat above a mantle "superswell" (Pribac and Davies, 1987). Such superswells are products of deep convective upwellings, expressed as topographic and geoidal highs and hotspot clusters having diameters on the order of 5000 km. The proposed Middle Proterozoic superswell caused thermal erosion of the Laurentian lithospheric mantle, injection of mantle melts into the continental crust, and extensive crustal melting. Components of uplift were both temporary, due to thermal expansion, and permanent, due to magmatic crustal underplating (McKenzie, 1984). Only the Archean cratons whose tectospheric roots had not been disrupted by, for example, Early Proterozoic subduction zones remained relatively unaffected; Early Proterozoic crust was extensively remelted.

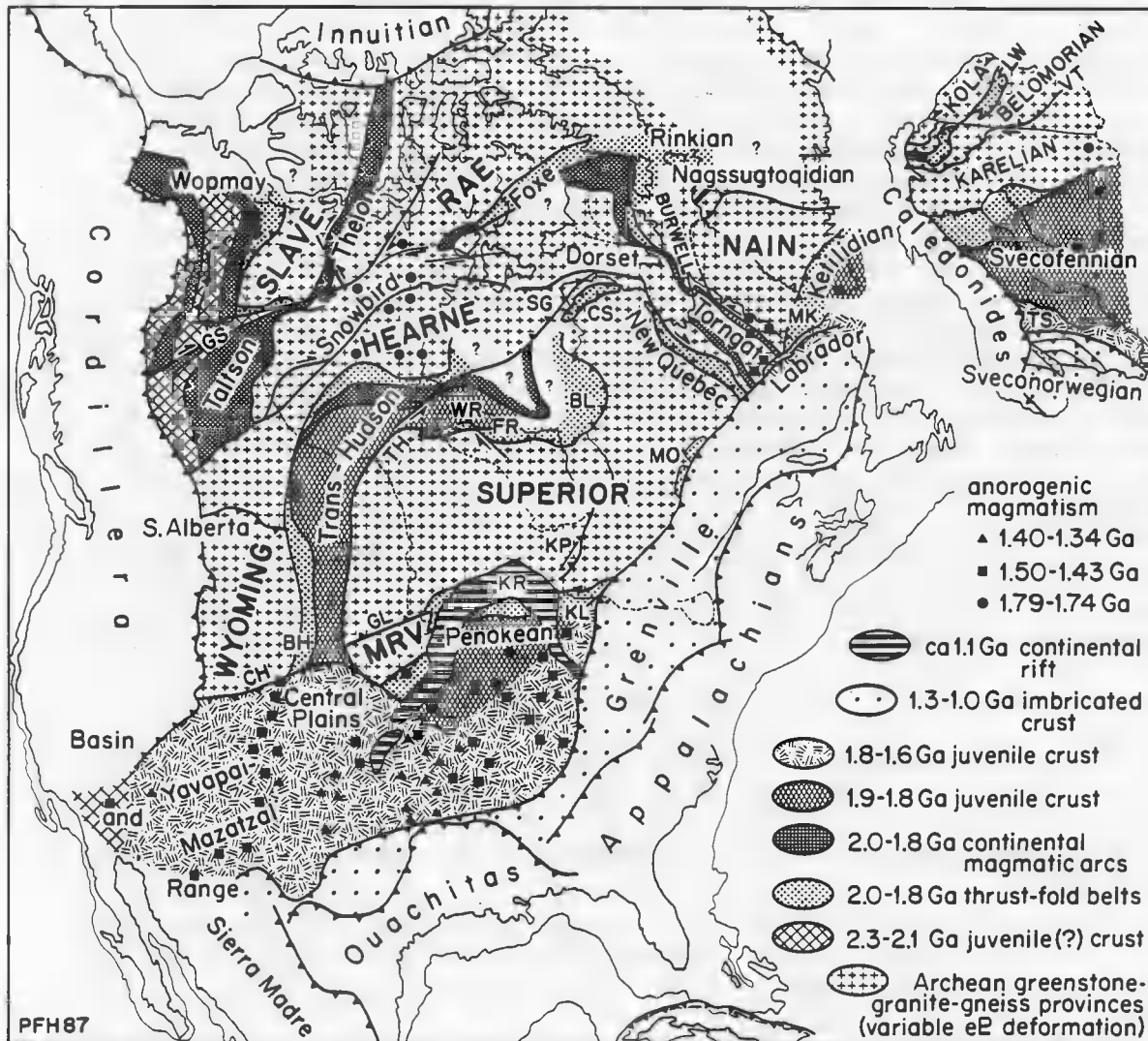


Figure 1. Precambrian tectonic elements of Laurentia and Baltica. Uppercase names are Archean provinces (former microcontinents); lowercase names are Proterozoic orogens. Greenland is restored prior to rifting from North America; Baltica is shown in a possible pre-Iapetus position. Abbreviations: BH=Black Hills; BL=Belcher foldbelt; CH=Cheyenne belt; CS=Cape Smith belt; FR=Fox River belt; GL=Great Lakes tectonic zone; GS=Great Slave Lake shear zone; KL=Killarney magmatic zone; KP=Kapuskasing uplift; KR=Keweenaw rift; MK=Makkovik orogen; MO=Mistassini-Otish basins; MRV=Minnesota River Valley terrane; SG=Sugluk terrane; TH=Thompson belt; TS=Transscandinavian magmatic zone; WR=Winisk River fault.

The protracted thermomagmatic assault by the superswell caused thinning and weakening of much of the Laurentian lithosphere, and has implications for injection of the Mackenzie dike swarm, deformation in the Grenville orogen, and magmatism in the Keweenaw rift. The 1.3 Ga Mackenzie dike swarm presents problems in accounting for its width (1800+ km) if caused by rifting and its length (2400+ km) if caused by a hotspot. Alternatively, the dikes may represent leakage from extensive intralithospheric melt-ponds emanating from the mantle upwelling. Dike orientation may only record the ambient intraplate stress regime, generally related to forces generated at plate boundaries. Accordingly, the dikes may parallel compressional stress trajectories generated by a coeval(?) orogen marginal to the Beaufort Sea, inferred from seismic reflection profiling. Recent seismic reflection profiling shows that much of the collisional Grenville orogen (1.25-1.0 Ga) is thrust imbricated to the base of the crust. The orogen is also unusual in lacking preserved foreland basins or other evidence of a flexural response to orogenic loading. These observations suggest a thin lithospheric mantle and low flexural rigidity during Grenvillian deformation. The 1.1 Ga Keweenaw rift has an extraordinary thickness (15-20 km) of basalt (its post-rift synclinal structure is due to volcanic loading). Theoretical calculations show that magma generation in rifts is critically dependent on potential asthenosphere temperature (White, 1987), consistent with anomalously hot asthenosphere beneath the rift.

Among the many unsolved problems regarding the early evolution of Laurentia are the following: (1) Did the Archean microcontinents have a common ancestry in a late Archean-early Proterozoic supercontinent? (2) Did Laurentia belong to a Middle Proterozoic supercontinent that broke up prior to the Grenvillian collision? (3) What was the Grenville hinterland that presumably separated from Laurentia during the opening of Iapetus?

References

- Hoffman, P.F., 1988, United plates of America, the birth of a craton: Early Proterozoic assembly and growth of Laurentia; *Annual Review of Earth and Planetary Sciences*, v.16, p.543-603.
- McKenzie, D., 1984, A possible mechanism for epeirogenic uplift; *Nature*, v.307, p.616-618.
- Patchett, P.J., and Arndt, N.T., 1986, Nd isotopes and tectonics of 1.9-1.7 Ga crustal genesis; *Earth and Planetary Science Letters*, v.78, p.329-338.
- Pribac, F., and Davies, G.F., 1987, Mantle superswells: regressions and rifts? (abstract); *Eos*, v.68, p.1451.
- St-Onge, M.R., Lucas, D.J., Scott, D.J., and Bégin, N.J., 1988, Thin-skinned imbrication and subsequent thick-skinned folding of rift-fill, transitional-crust, and ophiolite suites in the 1.9 Ga Cape Smith Belt, northern Quebec, in *Current Research, Part C; Geological Survey of Canada, Paper 88-1C*. In press.
- White, R.S., 1987, Volcanism and igneous underplating in sedimentary basins and rifted continental margins (abstract); XIX General Assembly, International Union of Geodesy and Geophysics, Vancouver, v.1, p.183.

THE STRATIGRAPHY AND PHYSICAL VOLCANOLOGY ASSOCIATED WITH THE
F-GROUP VOLCANOGENIC MASSIVE SULFIDE DEPOSIT,
STURGEON LAKE, NORTHWESTERN ONTARIO

George J. Hudak (Dept. of Geology, University of Minnesota -
Duluth, Duluth, MN 55812)

The F-Group volcanogenic massive sulfide deposit, situated 7 Km. west of the Mattabi massive sulfide deposit in the Archean Wabigoon greenstone belt, is located within an intensely altered succession of mafic to felsic metavolcanic rocks and associated intrusive rocks. This deposit yielded nearly 400,000 tons of Zn-Cu-Pb-Ag ore prior to its depletion in 1984. Detailed mapping and petrographic studies allow the volcanic succession associated with this deposit to be divided into several distinct lithological units. These are:

- a) bedded, scoria-rich volcanoclastic rocks which form the base of the volcanic succession and are up to 110 meters thick:
- b) massive, poorly sorted mesobreccia deposits which overlay the volcanoclastic rocks throughout the entire field area. These heterolithic deposits are up to 150 meters thick and contain from 20-70% basaltic and dacitic fragments which appear to be derived from volcanic rocks which underlie the scoria-rich volcanoclastic rocks:
- c) a series of quartz phyric, pumice-rich pyroclastic flow deposits which are up to 110 meters thick and are locally interfingered with, and grade into the mesobreccia deposits. These pyroclastic flows and associated ash tuffs form the immediate footwall rocks to the F-Group massive sulfide deposit:
- d) a 250 meter thick series of well bedded ash and quartz phyric, pumice-rich pyroclastic flow deposits. To the east, these rocks host the Mattabi orebody.
- e) a series of more massive pyroclastic flows which contain 1-6 mm diameter quartz and plagioclase crystals. These flows comprise the uppermost units associated with the F-Group orebody.

The scoria-rich volcanoclastic rocks are the reworked equivalents of a scoria cone/tuff cone deposit located immediately east of the field area, and are believed to have been deposited in shallow water. The mesobreccia and quartz crystal-rich pyroclastic flows are believed to represent deposits formed during the collapse of a caldera combined with simultaneous felsic volcanism. The F-Group massive sulfide deposit was formed prior to a second cycle of explosive volcanism that deposited the bedded, quartz-phyric, pumice-rich pyroclastic flows and ash tuffs which host the Mattabi massive sulfide deposit to the east. The uppermost quartz- and plagioclase-phyric pyroclastic flows represent the last phase of explosive volcanism associated with the caldera.

MICHIGAN KIMBERLITE PROVINCE

W. JARVIS

Jack Murphy, Trustee, P.O. Box 90, Crystal Falls, Michigan 49920

J. KALLIOKOSKI

Michigan Technological University, Houghton, Michigan 49931

The disclosure by Cannon and Mudrey (1981) of the presence of the Lake Ellen kimberlite in the Upper Peninsula of Michigan pointed to the possibility that the source of historical diamond finds in the Great Lakes region could be other than in the James Bay lowlands of Ontario as had been previously assumed. Jack Murphy, Trustee (Dow Chemical Company), with whom we are associated, has been actively exploring since 1982 for other expressions of the Lake Ellen kimberlite field, and has looked at the economic potential of those kimberlites that have been found. This paper reports on six additional kimberlites found, which occupy a north-west trending belt extending from the Powers/Hermansville area to Lake Ellen (Fig. 1).

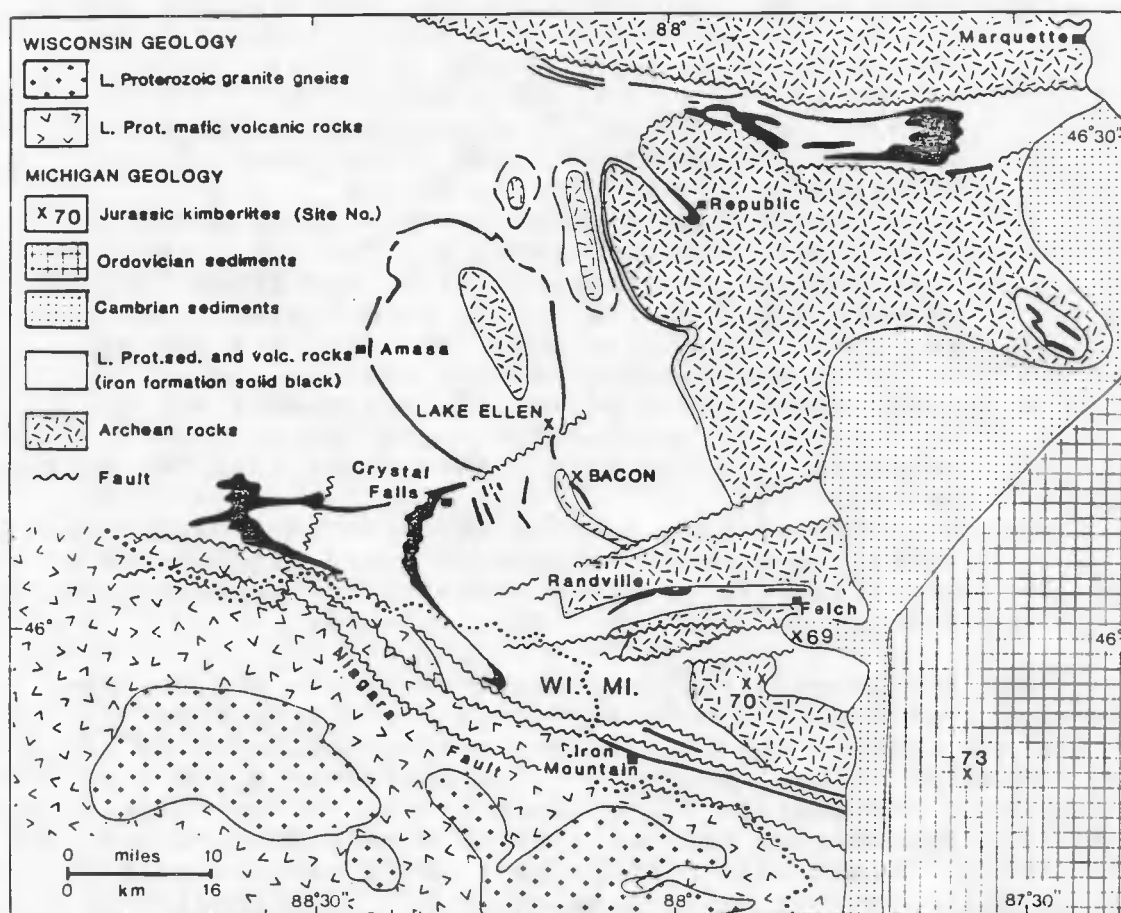


FIG. 1. Bedrock geology of the Marquette-Iron Mountain region of Michigan-Wisconsin, showing the location of known kimberlite bodies.

It is now generally accepted that in Michigan the Precambrian Shield is made up of two sutured Archean terranes across which were deposited lower Proterozoic passive margin and rift basin assemblages of sedimentary and volcanic rocks, some possibly 2.1 b.y. old. These rocks underwent a

period of tectonism estimated at about 1.9 b.y., and were cut by east-west striking post-orogenic diabase dykes. Thus, one requirement that the search for diamondiferous kimberlites be conducted on stable portions of cratonic blocks was satisfied.

In the region of our kimberlite finds the structures in the Archean basement and deformed Proterozoic cover trend from westerly to northwest (Fig. 1).

The Site 73 kimberlite intrudes flat-lying lower Paleozoic shallow sea basin margin sedimentary rocks. At one time this sedimentary cover extended to the west and northwest as evidenced by outliers at Limestone Mountain and by abundant xenoliths of lower Palaeozoic rocks in all the discovered kimberlites.

The Lake Ellen kimberlite was dated by Cannon and Mudrey as post lower Palaeozoic by the presence of Ordovician limestone xenoliths. The 6 additional kimberlites are also post lower Palaeozoic, some with Devonian fossils (J. Huml, personal communication, 1987).

Macrocrystal zircons (3mm) recovered from Site 73 mineral concentrates have been dated at 155 m.y. using the fission-track method (Craig Chesner, personal communication, 1987) and a potassium-argon age of 190 m.y. was obtained from phlogopite from the same kimberlite (Craig Smith, personal communication, 1987). Based on these age determinations and their similar modes of occurrence, we conclude that all of the kimberlites are Mesozoic, probably Jurassic.

The compositions of garnet and chromium spinel from kimberlite can be used as guides to the possible presence of diamond by comparing them (and their abundance) to the compositions of garnet and spinel occurring as inclusions in diamond and in known diamondiferous kimberlites (Gurney and Switzer, 1973; Gurney, 1984; Harte, et al, 1980; Sobolev, et al, 1973; Sobolev, 1984). Diamond has two proven parageneses: eclogitic and peridotitic. The garnet population at each of the kimberlites was examined for compositions comparable to those found in kimberlites containing diamonds of a known peridotitic paragenesis (Gurney's G-10 garnets). For the Lake Ellen and Bacon kimberlites, a preselection of grains was made to ensure that all color groups were represented. Garnets with diamond inclusion compositions, or even compositions with lower CaO and higher Cr_2O_3 than the lherzolite field, are rare (Fig. 2). McGee has reported a similar low G-10 population for Lake Ellen (McGee, 1987). For the Site 69, 70 and 73 kimberlites, only lilac, purple or mauve garnets were sent for analysis. This produced a plot with a bias toward garnet compositions falling near the G-10 field. However, a large amount of mineral concentrate was examined for the selection of these grains and, according to the Gurney criteria, the lack of a significant population of G-10 garnets suggest the pipes may not be highly diamondiferous (Gurney, 1984; Boyd and Gurney, 1982).

A number of chromium spinels from each of the Michigan kimberlites were also analysed but no spinels of diamond inclusion field compositions were found. Literature sources suggest that in diamondiferous kimberlites, up to about 12% of the spinel population falls in the diamond inclusion compositional field.

Based on our work we conclude that these particular kimberlites are unlikely to be economically diamondiferous and also, that they are not the probable specific source for the large diamond finds in Wisconsin. However, the presence of G-10 compositions in the garnet population does indicate that the source region for the kimberlite magma was within the diamond stability field of the upper mantle, as was also indicated by McGee and Hearn (1982), and that the potential for diamonds in other kimberlites in this area remains strong.

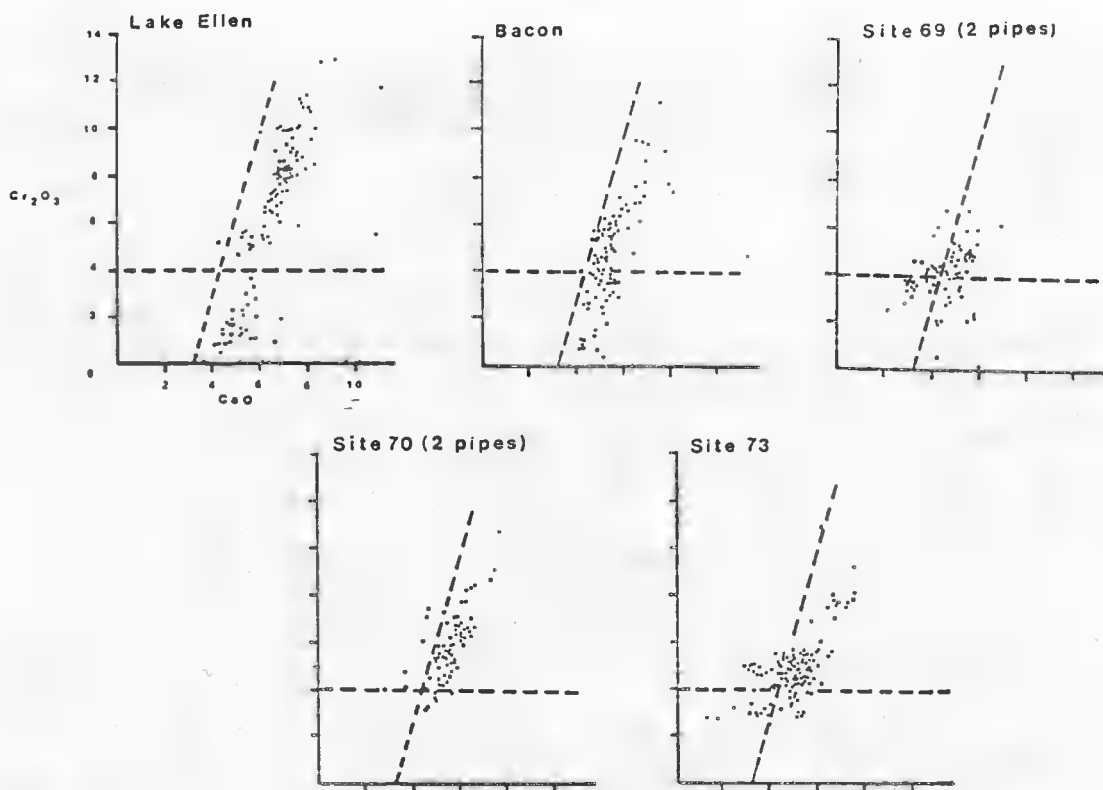


FIG. 2. CaO v. Cr_2O_3 plots for selected garnet grains from each of the kimberlites. The dashed lines correspond to the 85 percentile lines of Gurney.

References

- Boyd, F.R. and Gurney, J.J., 1982, Low calcium garnets: keys to craton structure and diamond crystallisation. Carnegie Institute, Washington, Yearbook, v. 81, p. 261-267.
- Cannon, W.F. and Mudrey, M.G., Jr., 1981, The potential for diamond-bearing kimberlite in northern Michigan and Wisconsin. U.S. Geol. Survey Circular 842, 15 p.
- Gurney, J.J., 1984, A correlation between garnets and diamonds in kimberlites, in Glover, J.E. and Harris, P.G., eds., Kimberlite occurrences and origin: a basis for conceptual models in exploration. University of Western Australia, Geology Dept. and Univ. Extension Publication.
- Harte, B., Gurney, J.J., Harris, J.W., 1980, The formation of peridotite suite inclusions in diamond. Contrib. Mineral. Petrol, v. 72, p. 131-190.
- McGee, E.S., 1987, Garnet xenocryst analyses: potential for diamonds in the Williams kimberlite, north-central Montana and the Lake Ellen kimberlite, northern Michigan. U.S. Geol. Survey Open-file Report 87-418, 15 p.
- Sobolev, N.V., 1984, Kimberlites of the Siberian platform: their geological and mineralogical features in: Glover, J.E. and Harris, P.G., eds., Kimberlite occurrence and origin: a basis for conceptual models in exploration. University of Western Australia, Geology Dept. and Univ. Extension Publication 8, p. 143-166.

GEOCHEMICAL STRATIGRAPHY OF THE HURONIAN CONTINENTAL VOLCANICS, ONTARIO: RELATIVE CONTRIBUTIONS OF MANTLE HETEROGENEITY, OPEN - SYSTEM MAGMATISM AND CRUSTAL FUSION

Wayne T. Jolly (Department of Geological Sciences, Brock University,
St. Catharines, Ontario, Canada L2S 3A1)

The 1500 m thick sequence of Huronian flood basalts at Thessalon, Ontario, contains interlayered low-Ti, enriched continental tholeiites and two distinct varieties of crustally derived rhyolite (1, 2). The stratigraphic succession is divided into four volcanic cycles, each of which includes early mafic and late felsic phases. Basalts of mafic phases were erupted from a progressively fractionating, periodically replenished magma source of the type envisaged by O'Hara and Mathews (3), probably located at the density discontinuity marking the boundary between the crust and lithospheric upper mantle. Magmas of the earliest volcanic sequence underwent simultaneous contamination by siliceous, depleted material of lower crustal affinities and gabbroic fractionation with an assimilation/fractional crystallization (AFC) ratio of 0.4. Subsequent cycles do not display AFC-type contamination, suggesting that a solid basaltic layer formed at the top of the main magmatic source body cutting off contact with the lower crust (see also 4).

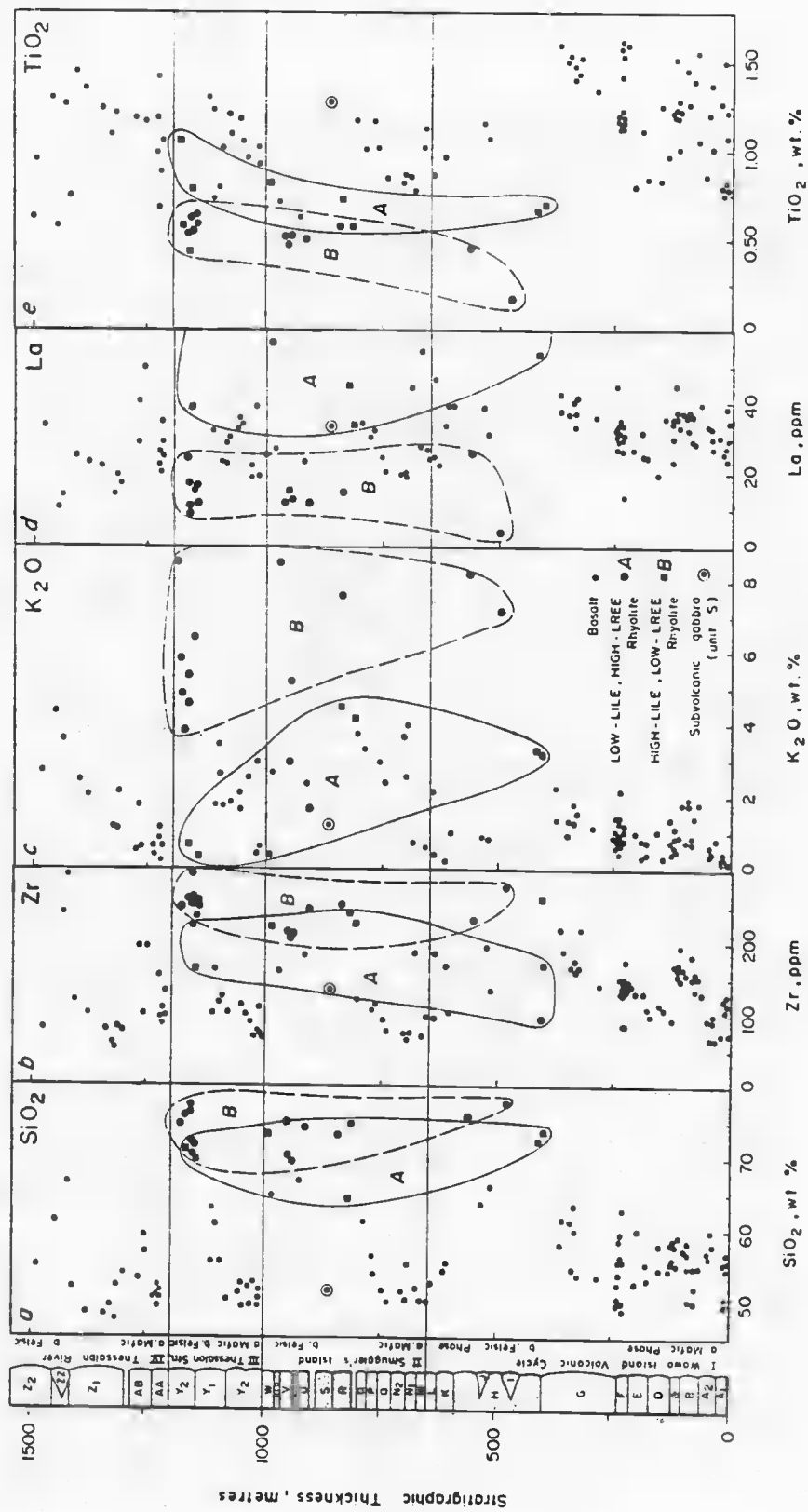
Crustal fusion during the mafic phase of each volcanic cycle eventually produced so much rhyolitic liquid that basalt magmas no longer passed freely to the surface; basalts are uncommon in felsic phases. When present they are invariably highly contaminated. The predominant contaminant was derived by an average of 20% fusion of high-LILE, relatively low-LREE leucogranitic upper crustal material (1), but low-LILE, high-LREE liquids from low-degree melting of depleted siliceous tonalite at deeper levels were also present. Resulting hybrid magmas form two mixing lines between basalt compositions and the individual rhyolite types; basalt-rhyolite mixing ratios as high as 40:60 are common in the central part of the stratigraphic section. During the final volcanic cycle, rhyolites were not erupted, and crustal contamination became less common, probably because volcanic vents, conduits and feeders had become insulated by marginal chilled zones, as suggested elsewhere (5).

The beginning of each successive volcanic cycle presumably occurred following crustal cooling during the interim, and was marked by replenishment of the main magma reservoir at depth and renewed mafic volcanic activity. Initial magmas of each cycle were relatively uncontaminated, but compositions of mafic end-members at any given Mg^* became progressively less siliceous and less enriched in LILE and LREE with time. For example, early flows display La/Y, Sr/Y, and Cu/Y ratios of 0.6, 6.0, and 0.8 respectively, compared to 1.0, 8.0, and 2.0 in central basalts and 1.2, 15, and 3.0 in late basalts. In addition, absolute TiO₂ content increased from 0.75 to over 1.25%, while Ti/Zr ratios gradually rose from 35 to stabilize at about 85 in late basalts. Enrichment of early basalts cannot be attributed to crustal contamination, since both Sr and Cu are also enriched in these basalts, while compositions of both upper and lower crustal contaminants, as reflected by compositions of the accompanying rhyolites, are highly depleted in these components. Therefore, the variations are considered to reflect heterogeneity in the lithospheric mantle source. Basalts of the first volcanic cycle were composed of the most enriched magma type. This liquid was subsequently progressively diluted in the main reservoir by influx of a new, less-enriched magma, giving rise to a mixing line between the two types. The original magma was largely flushed from the system by late stages of Huronian volcanism (6).

Both basalt types exhibit enrichment in incompatible element abundances, but negative anomalies for the more refractive lithophile elements, including Nb, P, Zr, and Ti, and positive anomalies for Sr on mantle-normalized diagrams are features characteristic of island arc tholeiite basalts (2). It is suggested that enrichment of the Huronian subcontinental lithospheric mantle occurred through ancient subduction of crustal material, probably during formation and consolidation of the continental crust. The Huronian basalts resemble, in both tectonic setting and geochemistry, widespread Mesozoic flood basalts erupted in association with continental break-up, including the Farrar Group of Antarctica (7), and the Parana and equivalent Etendeka continental basalts of south Brazil and Namibia (8, 9) respectively.

References

- 1) Jolly, W. T., 1987, Can. J. Earth Sci. 24, 1360-1385.
- 2) Jolly, W. T., 1987, Earth Planet. Sci. Lett. 85, 401-415.
- 3) O'Hara, M. J. and Mathews, R. E., 1981, J. Geol. Soc. London 138, 237-277.
- 4) Huppert, H. E. and Sparks, R. S. J., 1980, Contr. Mineral. Petrol. 75, 279-289.
- 5) Cox, K. G. and Hawkesworth, C. J., 1985, J. Petrol. 26, 355-377.
- 6) Jolly, W. T., 1988, Contrib. Mineral. Petrol. (in press).
- 7) Kyle, P. R., 1980, Contrib. Mineral. Petrol. 73, 89-104.
- 8) Petrini, R. et al., 1987, J. Petrol. 28, 701-726.
- 9) Hawkesworth, C. J. et al., 1984, Nature 311, 331-335.



STRATIGRAPHY AND PHYSICAL VOLCANOLOGY OF THE FOOTWALL ROCKS TO THE STURGEON LAKE MASSIVE SULFIDE DEPOSIT, NW ONTARIO

PETER K. JONGEWAARD, University of Minnesota-Duluth, Duluth,
Minn., 55812

The Sturgeon Lake massive sulfide deposit sits atop a 6 km. thick succession of mafic to felsic volcanic and volcanoclastic rocks of the Savant-Sturgeon Lake metavolcanic-metasedimentary greenstone belt. The ore deposit yielded 2.1 m.t. of high-grade Zn-Cu-Pb-Ag-Au ore from 1974 to 1980. Despite regional greenschist and local amphibolite grade metamorphism and variable amounts of hydrothermal alteration, seven distinct volcanic units have been identified in the footwall succession. This subdivision is based on preserved primary textures, fragment types, composition, and regional stratigraphic correlation.

Mafic volcanic rocks comprise the lowermost 3 km. of the footwall succession, and are composed of massive, brecciated, amygdaloidal, and pillowed flows. Pillows may consist of up to 70% rounded amygdules, indicative of shallow water extrusion. The mafic volcanic rocks are overlain by a thick (1 km.), laterally extensive heterolithic breccia, composed of angular lapilli- to block-sized mafic and felsic volcanic fragments set in a mafic matrix. This breccia is intercalated with, and overlain by a quartz-phyric pumice-bearing ash-flow tuff, which reaches a maximum thickness of 150 m. This tuff marks the first large-volume eruption of felsic material in the succession. The ash-flow tuff is succeeded upward by debris flow and bedded epiclastic deposits, which contain fragments of the underlying units as well as bomb-sized juvenile pumice. Overlying the debris flow deposits is a thick 1 km. sequence of massive to bedded quartz- and quartz/plagioclase-phyric ash-flow tuffs. Massive units are up to 250 m. in thickness, whereas bedded units consist of normally-graded 10-30 m. basal beds composed of crystals, lithic lapilli, and pumice overlain by thinly-bedded ash units. The top of this sequence is the immediate host to the Sturgeon Lake massive sulfide deposit. Thin amygdaloidal mafic to intermediate lavas cap the succession and form the hangingwall to the orebody. The volcanic succession is intruded by intermediate to mafic sill-like bodies which comprise up to 25% of the rocks in the area.

A major north-trending synvolcanic structure divides the area into two distinct stratigraphic sequences. To the west of the structure, basal mafic flows are overlain by the breccia-ash-flow tuff-debris flow sequence. East of the structure the basalts are immediately overlain by fragment-poor ash-flow tuffs which thin rapidly and pinch out eastward. It is believed this structure represents the eastern topographic margin of the Sturgeon Lake caldera which has been traced westward for up to 20 km. Owing to unique circumstances of regional deformation and erosion, both intracaldera fill and outflow facies resulting from caldera collapse can be studied in detail.

A LATE ARCHEAN CLASTIC SEQUENCE — FILL OF A FAULT-BOUNDED BASIN STRUCTURE

M.M. Kehlenbeck and B.E. Seemayer

Dept. of Geology, Lakehead University, Thunder Bay, Ontario P7B 5E1

North and west of Thunder Bay, Ontario, the Archean bedrock of the Wawa subprovince includes several exposures of clastic sedimentary and intercalated volcanic rocks. These clastic sequences form isolated outcrop areas of lenticular shape which delineate an 80 km long belt from Thunder Bay west to Shebandowan.

These rocks are commonly designated as a younger sequence compared to the Archean volcanic and sedimentary terrane with which they are in contact. The terms "Timiskaming" or "post-Keewatin" have been suggested for these clastic sequences (Macdonald, 1938; Shegelski, 1980). In most cases the designation of these rocks as a younger sequence is based on certain lithological similarities with established Timiskaming strata in the Abitibi belt (Quebec), and on structural and stratigraphic discontinuities along the contacts with "Keewatin" volcanic rocks.

More recently Borradaile and Brown (1987) have used the term "Shebandowan group" for clastic sedimentary rocks near Shebandowan. Their work shows that the rocks are isoclinally folded and that the deformation was accompanied by the development of a single tectonic and magnetic fabric. Based on bedding-cleavage relationships, Borradaile and Brown show that the folds, where traceable, have east-west axial surfaces and moderately to strongly curved hinge lines, and that locally the folds developed in inverted strata. They suggest that the "Shebandowan group" is at least partly in fault contact with the adjacent volcanic rocks ("Keewatin group"), although they were unable to locate exposures which would permit documentation of this relationship.

Corfu and Stott (1986) have reported precise U-Pb ages from rocks of the Shebandowan belt. Their results show that the clastic rocks of the "Shebandowan group" are about 40 Ma years younger than the adjacent "Keewatin" volcanic rocks. They suggest the age of deposition for the clastic rocks of Timiskaming-type at 2689 ± 3 Ma. This age was obtained from a latitic breccia representative of calc-alkaline to alkalic volcanic rocks which are interfingered laterally with terrestrial sediments suggesting contemporaneous volcanism and sedimentation. A porphyritic trondhjemite clast from a conglomerate which is part of the clastic sequence formed 2704 ± 2 Ma ago and represents a maximum age for deposition of the sequence. In contrast, an age of 2733 ± 3 from a porphyry sill is a minimum age for a sequence of older volcanic rocks exposed to the north.

The clastic sequence is composed of a variety of rock types which include sandstone, siltstone, greywacke, arkose, conglomerate, clastic volcanic rocks, and minor occurrences of iron formation. Spatially these rock types are intimately associated, and commonly several types occur in a single outcrop. Because of the complex nature of their distribution, it is not possible to map any particular rock type for any distance in the field.

In many outcrops the recognition of bedding is not difficult. However, it is typical to find marked variations in bedding attitudes from one outcrop to another as well as in a single exposure. These variations in bedding attitudes are commonly separated by small faults.

In the eastern portion of the clastic sequence, bedding of more consistent orientation can be traced in several outcrops. Here too, local way-up of the strata can be determined from graded beds and cross-bedding. Based on these observations, the rocks appear to indicate a synformal structure although no fold closures were observed in the field.

In most exposures, but particularly in those where fine-grained and semipelitic rocks occur, a continuous slaty cleavage is observable. This cleavage is also present in coarser grained rocks where it forms an anastomosing pattern.

In most outcrops of the clastic sequence, and particularly in the finer grained, well layered rocks, the bedding and continuous cleavage have been folded. In many exposures this small scale folding has led to the development of chevron folds possessing narrow hinge zones and straight limbs. In some outcrops, polyclinal folds with multiple hinges and non-parallel hinge lines have developed. In all cases these noncylindrical folds possess a subvertical axial planar crenulation cleavage which strikes between northeast and northwest. In general fold hinge lines plunge steeply northward.

Although the folds are best developed in the more laminated rock types, they are also present in the coarser clastic rocks. In some unstratified sheets of conglomerate, the individual clasts are buckled into folds with angular hinges, whereas folds in the matrix have hinges which are more rounded. In one case, refolding of earlier folds about north striking axial surfaces has been observed.

Near the contact with the metavolcanic rocks, many outcrops of the clastic sequence are cut by faults. These structures truncate the small-scale folds and all earlier structures. In typical outcrops several faults of variable orientation produce an anastomosing pattern dividing the outcrop into lensoidal portions in which previous structures show marked variation in orientation. It is not uncommon to find earlier structures in near orthogonal relationships between adjacent fault-bounded segments. Evidence for faulting is

particularly pronounced in rocks of the western part of the clastic sequence along the contact with the volcanic succession. Exposures of the contact occur here and the rocks show a marked development of a mylonitic schistosity.

Field evidence supports the fault relationship between the clastic sequence and the adjacent volcanic terrane. Along the western and southern margin, numerous outcrops of the contact provide direct evidence of faulting in the mylonitic schistosity developed in the rocks. Elsewhere, zones of fault breccia and truncations of regional structural trends and distinctive lithologies reflect this discordant relationship.

Internally, the rocks of the clastic sequence include a wide variety of types which are commonly in fault contact with each other in individual outcrops. Abundant small faults greatly obliterate earlier structural and stratigraphic relationships. Collectively these features may indicate that the clastic sequence as a whole represents a strongly imbricated down-faulted block.

In addition to the faulting, the clastic sequence differs structurally from the metavolcanic rocks. A north-south striking subvertical crenulation cleavage is axial planar to small scale north-plunging folds. The structures fold the continuous slaty cleavage as well as the bedding. This crenulation cleavage has not been observed in the adjacent volcanic rocks.

Mesoscopic folds in the rocks of the clastic sequence are rare, nor could such structures be determined from systematic observations of bedding-slaty cleavage relationships.

The clastic sequence may represent an outlier of younger rocks in fault contact with the volcanic terrane. Field observations to date suggest that the clastic sequence as a whole represents the filling of a fault-bounded basin structure. The tectonic history of this basin is complex and may have included periods of transtension and transpression which affected the Archean crust regionally and closely coincide with the boundary between the Quetico and Wawa subprovinces.

Borradaile, G.J. and Brown, G.H., 1987. The Shebandowan Group: "Timiskaming-like" Archean rocks in northwestern Ontario. *Canadian Journal of Earth Sciences*, 24, pp. 185-188.

Corfu, F. and Stott, G.M., 1986. U-Pb ages for late magmatism and regional deformation in the Shebandown Belt, Superior Province, Canada. *Canadian Journal of Earth Sciences*, 23, pp. 1075-1082.

Macdonald, R.D., 1938. *Geology of Gorham Township and vicinity*. Ontario Department of Mines, Annual Report, v. 48, part 3, 18 p.

Shegelski, R.J., 1980. Archean cratonization, emergence and red bed development, Lake Shebandowan area, Canada. *Precambrian Research*, 12, pp. 331-347.

EVIDENCE FOR DEVELOPMENT OF AN EARLY PROTEROZOIC OVERTHRUST-NAPPE SYSTEM IN THE PENOKEAN OROGEN OF NORTHERN MICHIGAN

KLASNER, J.S., Department of Geology, Western Illinois University and U.S. Geological Survey, Macomb, IL 61455; OJAKANGAS, R.W., Department of Geology, University of Minnesota, Duluth and U.S. Geological Survey, Duluth, MN 55812; SCHULZ, K.J., U.S. Geological Survey, MS 954, National Center, Reston, VA 22092; and LABERGE, G.L., Department of Geology, University of Wisconsin, Oshkosh, and U.S. Geological Survey, Oshkosh, WI 54901

Evidence for development of an Early Proterozoic thrust-nappe system is found in 1900-Ma rocks at several localities in northern Michigan. At Falls River in L'Anse, north-verging, recumbently folded slates and graywackes of the Michigamme Formation have nearly flat-lying, axial planar foliation (Sikkila, 1987, and Sikkila and Gregg, 1987). About 20 km south of L'Anse, flat-lying Early Proterozoic quartzite occurs at Canyon Falls. The quartzite is separated by thrust faults from stratigraphically higher slates, phyllites, and metagraywackes of the Michigamme Formation at Little Mountain and Taylor Mine. Bedding at Little Mountain and Taylor Mine is overturned toward the north and has steeply south-dipping foliation (see Fig. 1). At Plumbago Creek similar overturned slates and phyllites have steep south-dipping foliation that projects beneath Archean gneiss. A drill-hole about 10 km east of Taylor Mine penetrates Archean gneiss. The gneiss has shallow-dipping penetrative cleavage and is underlain by graphitic slate and quartzite, suggesting that the gneiss was overthrust above the slate.

About 110 km to the west, in Ironwood, Michigan, bedding in graywacke and slate of the Tyler Formation is oriented N75°E, 70°NW. These rocks have a prominent cleavage that is oriented N75°, 58°NW. The Tyler are part of a broad-scale, north-dipping homocline that formed during the 1100-Ma rift event. The Tyler strata are overlain by nearly concordant Keweenaw strata. Reorientation of the Tyler to its position prior to Keweenaw deformation shows subhorizontal bedding and gently south-dipping foliation compatible with a north-verging thrust-nappe system.

Thirty km east of Ironwood, hyaloclastites of the Emporer Formation have a foliation oriented N30°E, 30°SE. This shallow south dipping foliation is characteristic of the thrustured Early Proterozoic terrane described above and is interpreted to have been formed by the same north-verging thrust-nappe system that affected the Tyler and Michigamme Formations near L'Anse.

Such evidence for north-verging thrust faulting was previously recognized by Cannon and Klasner (1972), Klasner (1972), Cannon (1973), and Klasner (1978) and was interpreted as a decollement. The field guide for this meeting by Klasner and others, (1988) provides additional data on the nature of Early Proterozoic overthrusting in northern Michigan.

The data presented above span a distance of well over 100 km from Ironwood to L'Anse and indicate that Early Proterozoic rocks

and Archean gneiss of the Penokean orogen in this region are part of a broad-scale north-verging thrust-nappe system, probably the same thrust-nappe system as that described by Holst (1984), 300 km to the west in Minnesota.

REFERENCES

- Cannon, W.F., 1973, The Penokean orogeny in northern Michigan, In G.M. Young (ed.), Huronian stratigraphy and sedimentation: Geological Association of Canada Special Paper 12, p. 253-271.
- Cannon, W.F. and Klasner, J.S., 1972, Guide to Penokean deformational style and regional metamorphism of the Western Marquette Range, Michigan, In W.I. Rose (ed.), Field description and road logs: 18th Annual Institute on Lake Superior Geology, Houghton, Mich., p. B1-B38.
- Holst, T.B., 1984, Evidence for nappe development during the Early Proterozoic Penokean orogeny, Minnesota: Geology, v. 12, p. 135-138.
- Klasner, J.S., 1972, Style and sequence of deformation and associated metamorphism due to the Penokean orogeny in the western Marquette Range, northern Michigan: PhD. dissertation, Michigan Technological University, Houghton, Mich., 132p.
- Klasner, J.S., 1978, Penokean deformation and associated metamorphism in the western Marquette Range, northern Michigan: Geological Society of America Bulletin, v. 89, p. 711-722.
- Klasner, J.S., Sims, P.K., Gregg, W.J., and Gallup, Christina, 1988, A structural traverse across a part of the Penokean orogen illustrating Early Proterozoic overthrusting in northern Michigan: text and field guide, In K.J. Schulz (ed.), Field guides: 34th Annual Institute on Lake Superior Geology, Marquette, Mich. p. C1-C32.
- Sikkila, K.M., 1987, A structural analysis of Proterozoic metasediments, northern Falls River, Baraga County, Michigan: Master of Science thesis, Michigan Technological University, Houghton, Mich. 103 p.
- Sikkila, K.M. and Gregg, W.J., 1987, A structural analysis of Proterozoic metasediments, northern Falls River, Baraga County, Michigan (abs.): 33rd Annual Institute on Lake Superior Geology, v. 33, part 1, pp. 65-66.



See text for discussion.

CHEMOSTRATIGRAPHY OF THE LOWER DIVISION LAVAS OF THE MAMAINSE POINT FORMATION AND IMPLICATIONS FOR RIFTING TECTONICS

Klein, K.W., and Berg, J.H., Department of Geology, Northern Illinois University, DeKalb, IL 60115

Detailed study of exposures of the Mamainse Point Formation along the eastern shore of Lake Superior in Ontario reveals at least six recognizable units within the Lower Division of Annells (1973). The lowermost unit (~80 m thick) consists of olivine-phyric basaltic and picritic flows that are heavily dissected by calcite veins and appear to be more altered than flows higher up (olivines in this and all other units are altered to secondary minerals). This unit is overlain by a second unit (~200 m thick) of similar olivine-phyric flows, but without the ubiquitous calcite veins and appearing to be less altered. Near the middle of this unit are two or three very mafic flows that are komatiitic in terms of major-element chemistry. The upper part has several flows that contain small inclusions (≤1 cm) of wehrlite or spinel wehrlite (the olivine and possible spinel are altered to secondary minerals). Overlying this is the third unit, the very distinctive "daisy stone" (~25 m thick). This unit consists of 2-3 thin and one very thick flows of plagioclase-phyric ferrobasalt containing locally abundant 3-cm plagioclase spherulites. The fourth unit (~500 m thick) is composed of olivine-phyric basaltic and picritic flows. Especially in the lower part, this unit has much coarser olivine phenocrysts than the unit below the daisy stone unit (olivine phenocrysts in both units are typically skeletal). Above a transition zone of alternating olivine-phyric and plagioclase-phyric flows, is the fifth unit (~400 m thick) consisting of plagioclase-phyric basaltic flows. This unit is topped by the uppermost (sixth) unit (~400 m thick) consisting of aphyric basaltic flows interspersed with a few ophitic basalts. Near the base of this unit is the "basaltic breccia" noted by Annells (1973).

Thus far we have analyzed flows from the four oldest units and found major geochemical differences between them. The basal unit is dominated by low-TiO₂ (1.0-1.6 wt%) basalts and picrites, but these alternate locally with high-TiO₂ (up to 2.4 wt%) basalts and picrites. The second unit contains only the low-TiO₂ flows with generally less altered chemistry. The komatiitic flows mentioned above have MgO contents of 18-23 wt%. The daisy stone unit is a very-high-TiO₂ ferrobasalt, and analyses support an accumulation model for the plagioclase spherulites. The olivine-phyric flows above the daisy stone unit are high-TiO₂ (1.4-2.7 wt%) basalts and picrites. Figures 1, 2, and 3 show that except for the lowest unit the other units have distinct geochemical characteristics and trends. A plot of TiO₂ vs. flow # (Fig. 2) reveals some of the systematic internal variation within units, but also the profound and abrupt changes between most of the units.

These field and geochemical characteristics have allowed us to correlate this main section of the MPF that starts at Mica Bay with the Alona Bay section of the MPF based on reconnaissance field and compositional examination of the Alona Bay section. Contrary to the speculation of Annells (1973), the Alona Bay section starts high up in our second unit (alternatively, the first two units are extremely thinned at Alona Bay). In any event, although previously unrecognized, the daisy stone unit occurs relatively near the base of the Alona Bay section, and it is underlain by the low-TiO₂ olivine-phyric lavas and overlain by the high-TiO₂ olivine-phyric lavas. Rare small plagioclase spherulites are present in the Alona Bay daisy stone unit, but otherwise it is free of the abundant large spherulites that characterize the Mica Bay daisy stone.

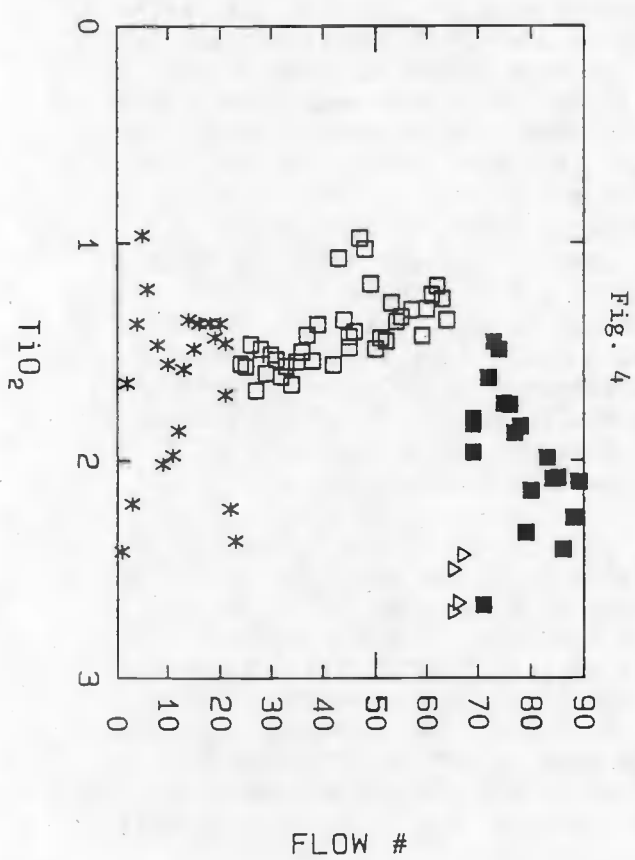
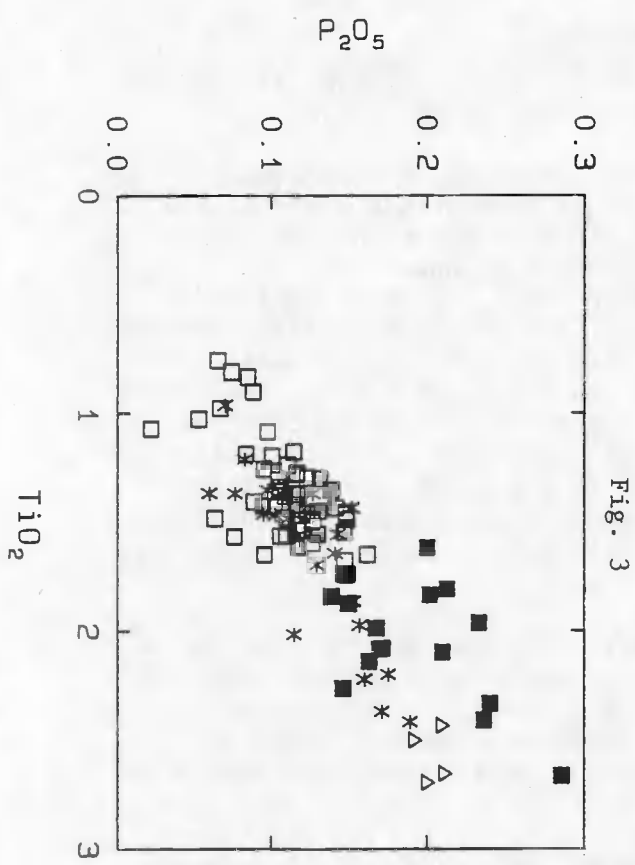
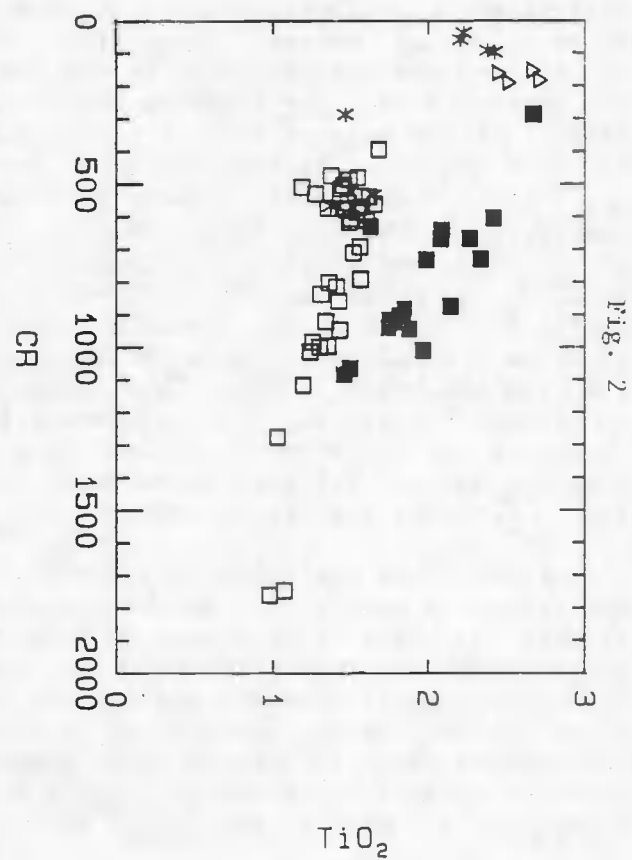
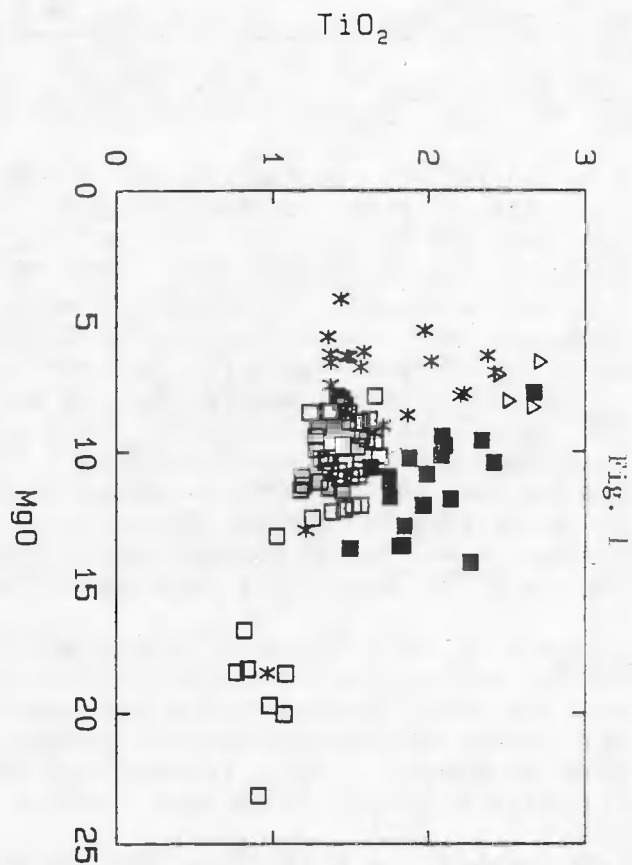
We believe that the magma chemistry of these primitive lavas, the progressive changes in magma chemistry within each unit, and the abrupt changes between units will ultimately provide important stratigraphically-controlled answers to major questions regarding the tectonic development, magmatic evolution, mantle structure and dynamics, and crustal integrity during the rifting process. For example, the lowermost unit contains lavas that may have originated from two separate mantle sources, both of which were very rich in LILE, but one (producing the high-TiO₂ lavas) richer than the other. Alternatively, some of the magmas were being modified by crustal assimilation while others were not, or at least less so. During the eruption of the second unit, only the less-enriched source was being tapped and magmas became progressively more primitive. Presumably the plumbing system was becoming better developed, allowing primitive lavas an ever-more direct route to the surface. This episode was abruptly terminated by the eruption of highly evolved ferrobasalts forming the daisy stone unit. After only 3-4 eruptions of this highly evolved magma, a new primitive magma system took over, erupting progressively less primitive lavas somewhat similar to the high-TiO₂ lavas of the basal unit. Because it appears difficult, if not impossible, to relate the three magma systems represented by the flows of the daisy stone and the units above and below, profound changes in magma sources and the crustal plumbing system must have been taking place across this interval. Perhaps the low-TiO₂ magma source was lithospheric mantle or involved a component of lithospheric mantle. Its termination could mark the point in time where the asthenospheric diapir finally eroded through to the base of the crust. This would have accelerated rifting of the crust and could have resulted in the disruption and tapping of crustal magma chambers containing highly evolved magmas, thus forming the evolved daisy stone unit. New magma generation would subsequently be derived solely from the asthenospheric subcontinental mantle. Alternative models are possible, and the constraints on these models will be greatly improved with isotopic results. Nevertheless, dynamic tectonic models for the Keweenaw rift will depend heavily on accurate and detailed chemostratigraphic studies of the erupted lavas.

REFERENCE

Annells, R. N., 1973, Proterozoic flood basalts of eastern Lake Superior: The Keweenaw volcanic rocks of the Mamainse Point area, Ontario, Geol. Surv. Canada Paper 72-10, 51 p.

NOTE FOR FIGURES

Asterisks = unit 1, open squares = unit 2, open triangles = unit 3 (daisy stone), solid squares = unit 4. Some of the samples from units 1 and 2 have not been analyzed for chromium.



THE BARABOO QUARTZITE: A NEW LOOK AT AN OLD PROBLEM

GENE L. LABERGE, Geol. Dept., UW-Oshkosh, Oshkosh, WI and U.S.G.S. and JOHN S. KLASNER, Geol. Dept., Western Illinois Univ., Macomb, IL and U.S.G.S.

In central and southern Wisconsin, quartzites, including the Baraboo Quartzite, represent the southernmost occurrence of Precambrian rocks in the Lake Superior region, but their stratigraphic and tectonic relations to the sedimentary rocks of the iron districts to the north is uncertain. Originally, the Baraboo Quartzite and associated slate, dolomite, and iron-formation were called "Huronian" and correlated with the iron-bearing rocks of the Lake Superior region (Weidman, 1904; Van Hise and Leith, 1911; Leith, and others 1935). Subsequently, Dalziel and Dott (1970), Smith (1978), Van Schmus (1978), and Greenberg and Brown (1983, 1986) suggested that the quartzites in southern Wisconsin are younger than 1,760 Ma and, therefore, substantially younger than the Proterozoic sedimentary rocks to the north. Deformation of the quartzites has been attributed to a postulated plate tectonic event that occurred 1,630 Ma ago and was buried beneath Paleozoic rocks to the south (Smith, 1978; Dott, 1983; Cambray, 1987).

Recent geologic studies (LaBerge and Klasner, 1986, and preparation) in central and southern Wisconsin suggest that the quartzite occurrences in this area are older than currently interpreted and that they are remnants of a major south-vergent thrust-fold system. Our studies, presented below and shown in Figures 1 and 2 suggest that the quartzite was present and was thrust southward before 1,760 Ma, and probably before 1,850 Ma.

At Baraboo, the relation of the quartzite to adjacent rhyolite is problematical. Dalziel and Dott (1970) suggested that the quartzite is stratigraphically above, and younger than, adjacent rhyolite, which is inferred to be 1,760 Ma. However, Stark (1930, 1932) suggested that rhyolite crops out on the upturned northern limb of the Baraboo Syncline, which indicates that the quartzite is older than the rhyolite. Although not unequivocal, our field investigations support Stark's (1932) interpretation. At Hamilton Mounds, the deformed quartzite is intruded by an undeformed granitoid dike dated at 1,764 Ma, which indicates pre-1,764 Ma deformation of the quartzite. At Vesper quarry, quartzite that has a steep-dipping tectonic fabric occurs within 3 m of an undeformed granite that is identical to granite at Cary Mound dated at 1,832 Ma; we infer that the 1,832-Ma granite intruded the already deformed quartzite. Along Hamann Creek in western Marathon County, quartzite boulders occur in a conglomerate that is interbedded with 1,850-Ma-old volcanic rocks (LaBerge and Myers, 1983). This requires the presence of a 1,850-Ma quartzite in central Wisconsin. Sillimanite-bearing quartzite xenoliths in the Wausau pluton probably represent uplifted high-grade basement rocks that are not exposed, but are inferred to underlie 1,850-Ma-old volcanic rocks of the region (LaBerge and Myers, 1984).

Therefore, the available stratigraphic evidence indicates that the quartzites in central and southern Wisconsin may be older than 1,850 Ma (Figure 1). Thus, they appear to pre-date the 1,850-Ma Penokean orogeny. We suggest that the quartzites represent remnants of a once-extensive sequence of Early Proterozoic platform sedimentary rocks deposited on the passive margin of an Archean craton, now exposed in central Wisconsin. The exact age of the sedimentary rocks is unknown, but, inasmuch as they appear to pre-date the Penokean Orogeny, they may be roughly equivalent to the Marquette Range Supergroup of northern Michigan. As shown in Figure 2, the platform sediments

are interpreted to have been thrust southward onto the Archean craton as it collided with the island arc rocks of the Wisconsin Magmatic terrane (see earlier studies of LaBerge, 1986; LaBerge and others, 1984a, b).

REFERENCES CITED

- Cambray, F.W., 1987, The Baraboo Syncline; The Shape and Refolding Explained as a Result of Superposition of Simple Shear on a Pre-Existing Fold: Abstract, G. S. A., Minneapolis, p. 192
- Dalziel, I.W.D., and Dott, R.H., jr. 1970, Geology of the Baraboo District, Wis.: Geol. and Nat. Hist. Survey Infor. Circular 14, 164 p.
- Dott, R.H., Jr. 1983, The Proterozoic red quartzite enigma in the north-central United States: Resolved by plate collision? G. S. A. Memoir 160.
- Greenberg, J. K., and Brown, B.A., 1983, Middle Proterozoic to Cambrian rocks in central Wisconsin: Anorogenic sedimentary and igneous activity: Wis. Geol. and Nat. Hist. Survey Field Trip Guide Book No. 8, 50 p.
- Greenberg, J.K., Brown, B.A., and Medaris, L.G. Jr., 1986, The Wolf River Batholith and Baraboo Interval: Guidebook Field Trip 1, 32nd Annual Inst. on Lake Superior Geology, Wisconsin Rapids.
- LaBerge, G.L., 1986, The Proterozoic Geology of the Lake Superior Region. in LaBerge, G.L. and Mode, W.N., Guidebook. 50th Annual Tri-State Field Conference.
- LaBerge, G.L., and Klasner, J.S., 1986, Evidence for a major south-directed Early Proterozoic thrust sheet in south central Wisconsin: Abstract, G. S. A. San Antonio, TX.
- LaBerge, G.L., and Klasner, J.S. (in preparation), Major south directed thrusting of Early Proterozoic quartzites in south central Wisconsin: Implications of the Penokean Orogeny.
- LaBerge, G.L., and Myers, P.E., 1983, The Precambrian geology of Marathon County, Wis.: Wis. Geol. and Nat. Hist. Survey Info. Circular 45, 88p.
- LaBerge, G.L., and Myers, P.E., 1984, Two early Proterozoic successions in central Wisconsin and their tectonic significance: G. S. A. Bull. pp. 246-253.
- LaBerge, G.L., Schulz, K.J., and Myers, P.E., 1984a, The plate tectonic history of central Wisconsin: Abstract. 30th Annual Inst. on Lake Superior Geology, Wausau, p. 25-27.
- LaBerge, G.L., Schulz, K. J., and Myers, P.E., 1984b, "Early Proterozoic Plate Tectonics: Evidence from north central Wisconsin," Abst. G. S. A. Reno, NV.
- Leith, C.K., Lund, R.J., and Leith, A. 1935. Pre-Cambrian rocks of the Lake Superior region, with revised geologic maps. U.S.G.S. Prof. Paper 134.
- Smith, E.I., 1978, Precambrian Rhyolites and Granites in South-Central Wisconsin: Field Relations and Geochemistry: Geological Society of America Bulletin, vol. 89, pp. 875-890.
- Stark, J. T., 1930, Pre-Cambrian water-laid tuff in the Baraboo, Wisconsin, District.: Jour. Geol., Vol. 38, pp. 466-471.
- Stark, J.T., 1932, Igneous rocks in the Baraboo District, Wisconsin: Jour. Geol., Vol. 40, pp. 119-139
- Van Schmus, W.R., 1978, Geochronology of southern Wisconsin rhyolites and granites; Geoscience Wisconsin, Vol. 2, p. 19-24.
- Van Hise, C.R., and Leith, C.K., 1911, Geology of the Lake Superior Region. U.S. Geological Survey Monograph 52.
- Weidman, S., 1904, The Baraboo Iron-Bearing District of Wisconsin: Wisconsin Geological and Natural History Survey Bulletin No. Xiii, 190 p.

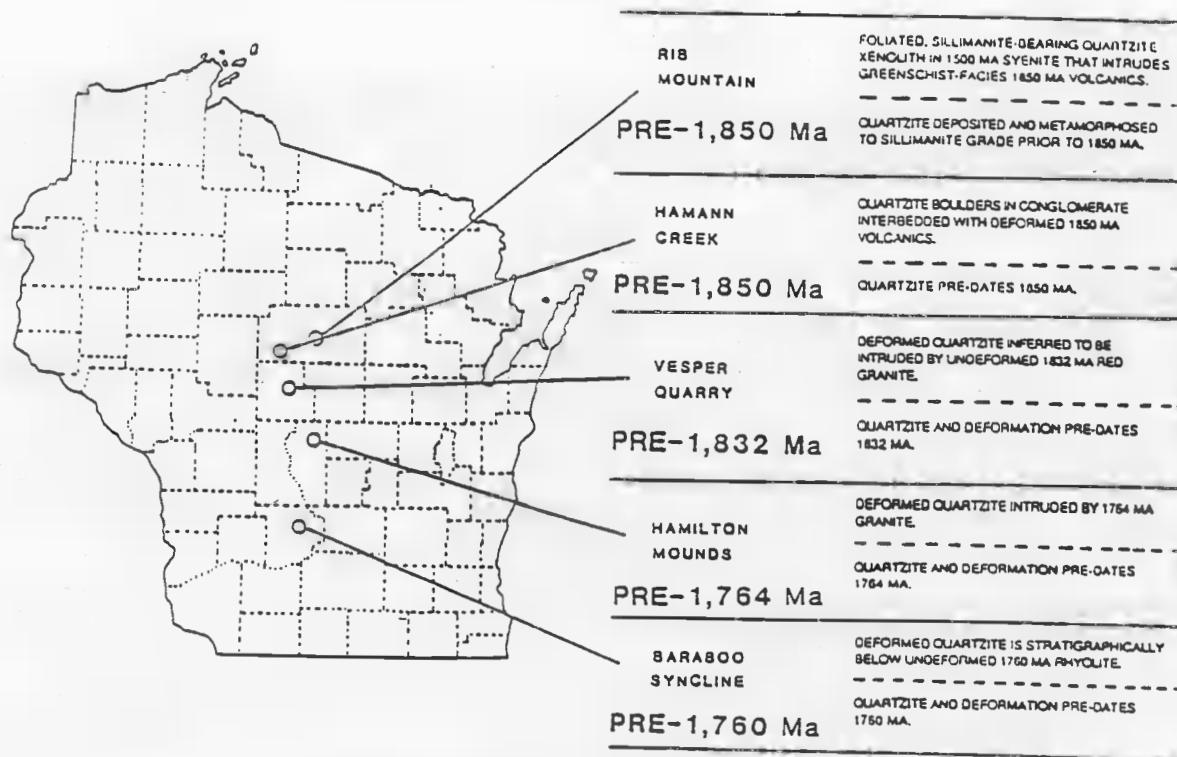


Figure 1. Location map and age relationships of quartzites in central and southern Wisconsin.

QUARTZITES OF SOUTHERN WISCONSIN

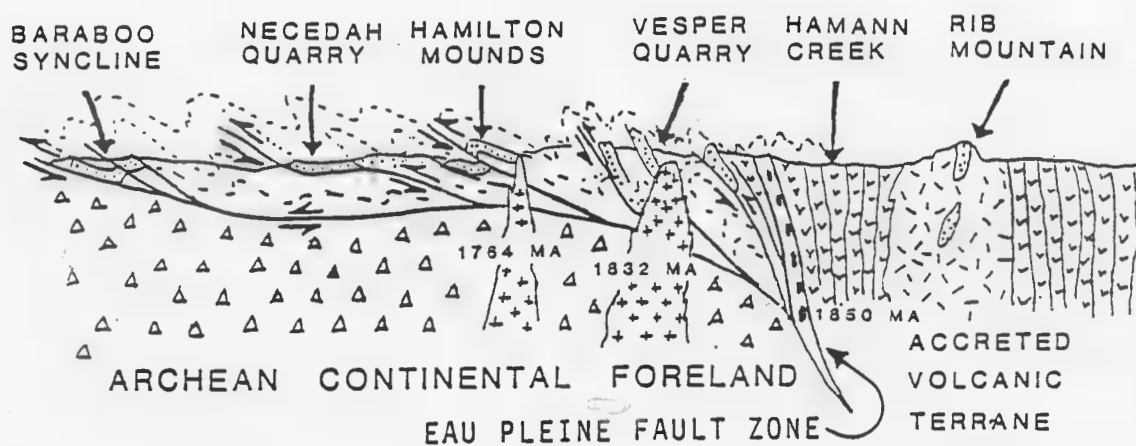


Figure 2. Diagrammatic cross-section of the proposed tectonic relationships of the southern Wisconsin quartzites.

PALEOMAGNETISM OF THE CLAY-HOWELLS CARBONATITE AND KEWEENAWAN MOTION ON THE KSZ

Lewchuk, M.T., and Symons, D.T.A., Department of Geology, University of Windsor, Windsor, Ontario, Canada N9B 3P4

The Clay-Howells Complex is located approximately 130 km east of Hearst, Ontario, at $49^{\circ}50'N$, $82^{\circ}05'W$ within the north end of the Kapuskasing Structural Zone (KSZ) of the Superior Province of the Canadian Shield. It is a large oviform pluton of $\sim 16 \text{ km}^2$ that is composed dominantly of syenite with minor carbonatite. It was emplaced into an Archean gneissic terrain of the amphibolite to granulite facies with Middle Precambrian diabase dikes. The complex is Late Precambrian in age ($\text{Rb/Sr } 1072 \pm 16 \text{ Ma}$) with a relatively fresh unmetamorphosed texture. Field and geophysical data indicate that the complex was probably formed by the passive intrusion of several magmatic pulses with similar compositions. A late fault may cut the northeast corner of the complex.

Detailed AF and thermal demagnetization of 194 specimens from 21 sites (18 from the intrusion, two from the dikes and one from the host gneisses) was completed using a CTF cryogenic magnetometer in a shielded room.

The 18 syenite sites define a consistent unit mean direction of 294.2° , 27.1° ($N = 18$, $k = 26$, $\alpha_{95} = 7.0$) which yields a pole position of $178.8^{\circ}E$, $26.5^{\circ}N$ ($D_p = 4.1$, $D_m = 7.6$) for the Clay-Howells Complex. A rudimentary contact test with the three Archean sites proved inconclusive. The scatter of the site means about the unit mean direction does not indicate a geographical bias so that post-intrusive movement along the fault - if any - did not produce tilting rotations.

The pole for the intrusion is concordant with the apparent polar wander path for Keweenawan rocks of Palmer and Davis (1987). It plots at approximately $1075 \pm 10 \text{ Ma}$ on the Logan Loop which is in agreement with the Rb/Sr age of $1072 \pm 16 \text{ Ma}$ for the Clay-Howells Complex. Therefore the conclusion is that the complex records an untilted, primary remanence. Its concordant pole indicates that there has been no significant uplift or rotation of the KSZ since the intrusion of the Clay-Howells Complex and that all significant geotectonic activity on the KSZ must predate $1072 \pm 16 \text{ Ma}$.

Geology, Structure and Mineralization of the Reany Lake Area, Marquette County, Michigan

Mary L. MacLellan and Theodore J. Bornhorst (Department of Geology and Geological Engineering, Michigan Technological University, Houghton, Michigan 49931)

During the summer of 1987 a 5 mi² area of the Marquette Greenstone Belt was mapped at a scale of 1:6000. This area includes Section 36, T49N, R27W, Section 31, T49N, R26W, Section 1, T48N, R27W, and Sections 6,7, T48N, R26W. The Reany Lake Area is outlined in Figure 1 below.

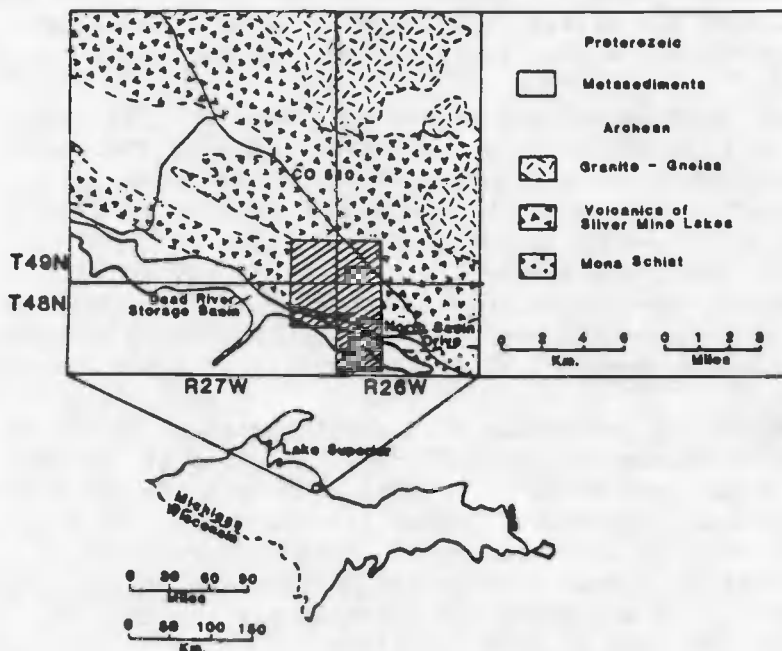


Figure 1.
Regional geology
and location map of
the Reany Lake area.

This study was undertaken in order to extend detailed mapping of the northern Marquette Greenstone Belt to the east. Previous detailed mapping has been done to the west of this area by Owens and Bornhorst (ILSG 1985), Johnson et.al. (ILSG 1987) and Baxter et.al. (ILSG 1987). Nomenclature of the units is still in a process of evolution but has been retained from one study to the next as much as possible. Figure 2 shows the stratigraphic correlation of the units identified in the Reany Lake area. The majority of the area is composed of Archean pillowed basalts interbedded with two mudflow breccias and an iron formation and intruded by Archean gabbro and rhyolite dikes. Mapping in this area extends nearly 2000' lower into the section than previous detailed studies due to the pinch out of a downfaulted block of Michigamme Formation.

With the exception of the lower breccia member and the bottom several thousand feet of pillowed basalt, the majority of the Archean volcanics and intrusives can clearly be correlated to the west. This is especially true of the Iron Formation Member and the Breccia Member of Reany Lake which persist, relatively unchanged, for up to four miles to the west of this area (Owens and

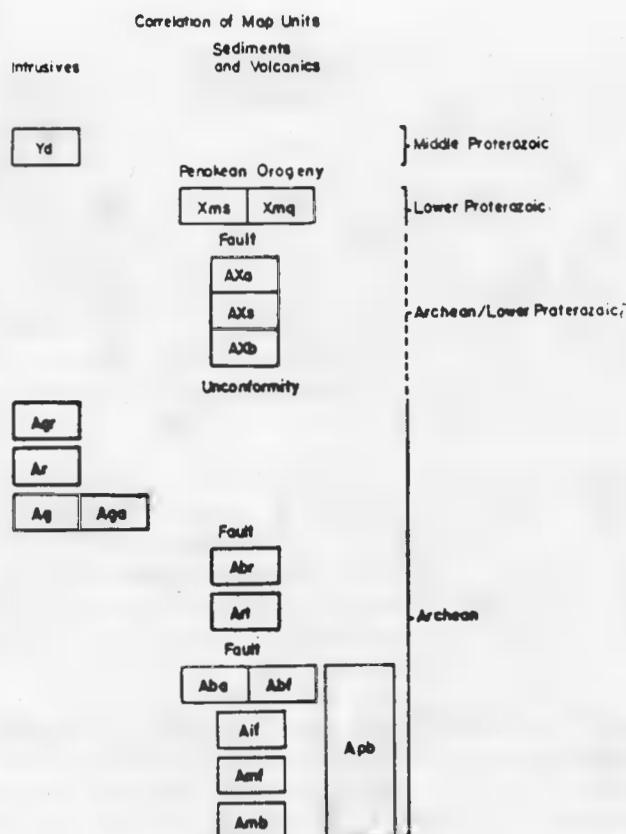
Bornhorst, ILSG 1985, Baxter et.al., ILSG 1987). Other units in the upper part of the Archean sequence can also be traced but they vary in character. To the west, there appears to be a greater number of recognizable pillow structures. To the west, there is a greater amount of quartz and carbonate alteration whereas in the Reany Lake area sericite and chlorite are common. Owens and Bornhorst (ILSG 1985) mapped a Laminated Schist Member, composed of laminated phyllitic and schistose volcanics, this is now correlated with the Altered, and Foliated Basalt Varieties of the Pillowed Basalt Member. The Reany Lake area includes a lower breccia unit stratigraphically below detailed studies to the west. It is called the Breccia Member of Bismark Creek, a polymictic breccia which lies along a major NW-SE trending shear zone. This unit is truncated by gabbro and it is uncertain whether it continues to the west of the Reany Lake area.

The Archean volcanic and intrusive rocks are unconformably overlain by the Reany Creek Formation, this unit is discussed in detail by Small and Bornhorst (ILSG 1988). To the south of the Reany Creek Formation is an upfaulted block of highly foliated Archean pillowed basalts and rhyolites which pinches out to the west. The relative age is uncertain. The entire area is overlain by slates of the Michigamme Formation. All of the preceding units have been cut by Middle Proterozoic Keweenaw diabase dikes.

All pre-Keweenaw rocks have been metamorphosed to greenschist facies. The Archean units typically have a foliation which strikes N70°W and is near vertical to steeply north dipping. The gabbro and rhyolite dikes commonly parallel this trend. Several generations of faults are evident in the Reany Lake area. The older (Archean) faults tend to parallel the trend of foliation and are quite continuous. They are marked by 10-100 foot wide zones of very high foliation and abundant alteration. The older faults are frequently truncated or off-set by later (Archean but possible reactivated during the Lower Proterozoic). N-S trending faults. These younger faults are reflected by 10-50 foot wide zones of moderate to strong foliation and are frequently marked by distinct ravines.

Evidence favoring precious metal mineralization in the Reany Lake area appears to be less abundant than to the west. Mineralization occurs primarily as disseminated sulfides within altered country rocks. There are very few quartz-carbonate-sulphide veins which are abundant in the areas to the west. Mineralization is most abundant adjacent to the major NW-SE trending shear zones and next to or within the rhyolite dikes. Metallic minerals generally consist of disseminated pyrite and widely scattered chalcopyrite.

This project was funded by the Michigan Geological Survey and Michigan Technological University.



Yd	Keweenaw Diabase
Xms/q	Michigamme Formation (Slates/Quartzites)
	Reany Creek Formation
AXa	Undifferentiated
AXs	Slates
AXb	Basal Conglomerate
Agr	Granodiorite of Rocking Chair Lakes
Ar	Rhyolite Intrusive of Fire Center Mine
Ag	Gabbro of Clark Creek
Aga	Altered Variety
Abr	Undifferentiated Foliated Pillowed Basalt and Rhyolite
Art	Highly Foliated Rhyolite
	Volcanics of Silver Mine Lakes
Apb	Pillowed Basalt Member
Aba	Altered Basalt Variety
Abf	Highly Altered and Foliated Basalt Variety
Aif	Iron Formation Member
Amf	Breccia Member of Reany Lake
Amb	Breccia Member of Bismark Creek

Figure 2. Stratigraphic Correlation chart for the Reany Lake area.

A SUBMERSIBLE DIVE ON SUPERIOR SHOALS: PLANS AND PROSPECTS

M.L.Manson & H.C.Halls, Dept. of Geology, University of Toronto, Erindale Campus, Mississauga, Ontario, Canada L5L 1C6

A review is given of a planned Geological and Geophysical study of the Superior Shoals, Lake Superior undertaken as part of the July 1988 Great Lakes Manned Submersible Program (NOAA National Underwater Research Program). Dives are to be carried out using a NOAA 2600 ft submersible for the purpose of orientated sample collection with, it is hoped, supplementary dredge sampling and photography from a tethered ROV, over a period of one to one and a half days. A concurrent series of side scan sonar and ship-borne magnetometer surveys will provide important bathymetric and geological data.

The Superior Shoals lie at the intersection of the Isle Royale and Thiel faults and occur about half way along the Trans-Superior Tectonic Zone defined to the north by the Slate Islands crypto-explosion structure and a line of intrusive alkaline complexes. The shoals are known from previous dredging and bathymetric work to consist of a northern ridge of red and grey sandstones and a southerly one composed of amygdaloidal basalt. These lithologies are consistent with Middle to Upper Keweenawan volcanic and clastic assemblages. The shoals represent the only outcrop of these rocks within a 60 kilometer radius in Lake Superior.

Priorities of the project will be;

1. To further understanding of the stratigraphy and structure of the eastern Lake Superior Basin, particularly in relation to the Trans-Superior Tectonic Zone and to recently acquired GLIMPCE seismic reflection profiles.

2. To investigate anomalous palaeomagnetic signatures suggested from crudely orientated chips collected previously by surface scuba dive. Data gained from these suggest a reversed magnetisation for the Keweenawan volcanics with a curious overprint of unknown origin which may be due to reheating effects (due to intrusions or to overlying normally magnetised flows similar to those on Isle Royale) or may be related to the Slate Islands explosive event. A further program of collection will be aimed at resolving these questions and will further knowledge of Keweenawan faulting, alkaline complexes and diatremes in the area.

3. To study aspects of native copper mineralisation reported (Kirkham & Franklin 1981) from samples dredged by the 1980 Cousteau expedition and models of basin wide fluid motion.

Work will be done in co-operation with R.V. Kirkham & J.M. Franklin, Geological Survey of Canada (copper mineralisation, bedrock geology), J. Klasner, Western Illinois University (rock fabric), and W.C. Kelly, University of Michigan (metamorphic phase equilibria, fluid inclusions and stable isotope).

Finally, an overview of the mechanical problems of underwater, remote oriented sample collection will be given.

COMPARISON OF TWO PARTS OF
THE DEAD RIVER-ISHPEMING GREENSTONE BELT:
EVIDENCE FOR CORRELATION OF VOLCANIC STRATIGRAPHY
by

G. Bradford Margeson, John W. Norby,
Robert A. Brozdowski, Alan S. Carter, Bruce A. Bouley
CALLAHAN MINING CORPORATION
EXPLORATION DEPARTMENT
25 Industrial Park Road
Negaunee, Michigan 49866

Detailed geologic mapping by Callahan Mining Corporation in the Dead River-Ishpeming Greenstone Belt has shown similarities in volcanic-sedimentary stratigraphy and intrusive events between 1) the west end of the south arm of the belt, and 2) the south half of the north arm of the belt.

The west end of the south arm of the belt comprises, from WNW to ESE, a consistently southeastward-facing sequence of 1) pillowed to massive basalt, subordinate basalt tuff, associated hypabyssal gabbroic sills and dikes, and minor mafic graywackes; 2) a zone of interlayered basalt, dacite tuff, and porphyritic hypabyssal dacite sills; 3) dacite tuff, which hosts a discontinuous trend of banded quartz-magnetite iron formation and quartzose graywacke; 4) volcanic conglomerates and tuff breccias. Fine grained serpentized peridotite strikes northeast and cuts the overall mafic to felsic transition at an acute angle. A northeast trending line of granitoid plugs intrudes the above mafic section. The extreme northwest and west parts of the basalt section, in proximity to the bounding granitoid terrane, is at amphibolite facies, the remainder of the above section is at greenschist facies.

The south half of the north arm of the belt comprises, from north to south, a consistently south facing sequence of 1) pillowed basalt, subordinate basalt tuff, and hypabyssal gabbroic sills; 2) a zone of interlayered basalt, mafic graywacke, hypabyssal porphyritic dacite intrusions transitional to dacite tuff, and a discontinuous trend of quartz-magnetite iron formation; 3) dacite tuff and porphyritic hypabyssal dacite intrusions. An east trending line of granitoid plugs intrudes the mafic section. The northernmost part of the basalt section is at amphibolite facies, the more southerly part of this arm is at greenschist facies.

The data suggests that the above two sequences have similar volcanic-sedimentary rock successions, intrusive events, facing directions, and metamorphic gradients. Although minor differences exist between the two sequences, the strong similarities suggest a common heritage. It is proposed that these two presently spatially separated sequences of Archean rocks were originally on-strike parts of the same terrane which has been separated and somewhat rotated by opening of the early Proterozoic Dead River Basin.

Comparison of the Keweenaw and Gregory Rifts from the Study of Teleseismic Delay Times and Bouguer Gravity

R.P. Meyer and W.V. Green, Department of Geology and Geophysics,
University of Wisconsin-Madison

Parameters that can be equally well studied in a billion-year-old rift and an active modern continental rift are the focus of an ongoing study in the midcontinent Keweenaw rift in the vicinity of the Petty-Ray profile northwest of Minneapolis and in the Gregory rift in the region of greatest uplift, northeast of Nairobi, Kenya. The parameters being used are teleseismic delay times of near-vertically-arriving waves from distant earthquakes and Bouguer gravity. The data show that the slope of the regression of delay time on Bouguer anomalies is five times as steep for African data as for midcontinent data. Why are the seismic delays per milligal so much greater in Africa? We believe that the answer lies in the existence of partial melt underlying the active rift. Further, in the Keweenaw rift we find that the slope of the regression of delay times on Bouguer anomalies is typical of other older tectonic features, such as the Sierra Nevada.

Other significant results are that these rifts are asymmetric features consistent with a model employing alternating half-grabens. We find this at the Gregory rift, and note that GLIMPCE and other seismic profile data across Lake Superior also support an alternating half-graben Keweenaw rift model. We also find as much variation in delay time along the Gregory rift as across it.

BEDROCK GEOLOGY OF THE SUPERIOR MAP SHEET, WISCONSIN

M.G. Mudrey, Jr., and B.A. Brown, Wisconsin Geological and Natural History Survey, 3817 Mineral Point Road, Madison, WI 53705, (in cooperation with the U.S. Geological Survey)

ABSTRACT

Reconnaissance mapping, examination of newly acquired drill core, and preliminary reanalysis of geophysical data in northwestern Wisconsin is in progress in cooperation with the U.S. Geological Survey as part of the COGEOMAP program. Initial work has resulted in a new preliminary 1:250,000 bedrock geologic map. The broad lithologic units on the new map do not differ significantly from those on previous maps; however, the relationship and significance of the various units has changed. Archean metavolcanic rock, granite, and gneiss occupy a southwest trending belt south of the Gogebic Range. The southeast corner of the map sheet is underlain by Early Proterozoic metasedimentary rock, mafic to intermediate volcanic rock, and iron formation. The Early Proterozoic succession on the Gogebic Range which is probably contemporaneous in age with the rock to the southeast in the Mercer Butternut area is in turn unconformably overlain by Middle Proterozoic Keweenaw volcanic rock. A reevaluation of the tectonic setting of the upper Keweenaw sedimentary rock succession is discussed in a separate presentation at this meeting (A.B. Dickas and M.G. Mudrey, Jr.).

The regional unconformity between the Chocelay Group (represented on the west Gogebic Range by the Bad River Dolomite) and the Menominee Group (represented by the Palms, Ironwood and Tyler Formations) is confirmed, suggesting regional folding, uplift and erosion during the Early Proterozoic; the regional unconformity between the basal Keweenaw Bessemer Quartzite and the Tyler Formation indicates deformation, uplift and erosion prior to deposition of the Bessemer. Subsequently, the units were tilted to the north into the Lake Superior syncline.

Future work will concentrate on establishing the relationship between the tectonic history of the Early Proterozoic rock of the Gogebic Range and that in the southeast corner of the area, south of the intervening block of Archean rock. An additional goal of this project is to better map the Archean rock and clarify the relationship between the granite-greenstone terrane south of Hurley and the gneiss exposed further to the southwest.

MIDCONTINENT RIFT MODEL BASED UPON
GREGORY RIFT TECTONIC AND SEDIMENTATION GEOMETRIES

M.G. Mudrey, Jr., Wisconsin Geological and Natural History Survey,
3817 Mineral Point Road, Madison, WI 53705, and
A.B. Dickas, University of Wisconsin-Superior, Superior, WI 54880

ABSTRACT

Middle Proterozoic tepetate-type sedimentation growth geometries on a major scale have been identified within the Midcontinent Rift System from Lake Superior reflection profiles (GLIMPCE), on-shore Wisconsin drill core (Bear Creek Mining Co.), and outcrop analysis. These geometries are in the form of structurally independent basins in which differential listric movement along axially-oriented fault systems have created sedimentation wedges of alternating isopach polarity. Within the area of study from northwestern Wisconsin into the eastern sector of Lake Superior this regional geologic setting appears to be structurally similar to that reported along the Gregory Rift of Kenya, Africa.

Midcontinent Rift tectonic models published since 1956 have emphasized a centrally positioned horst bounded by parallel faults within a broader graben or rift. These systems formed in the inner border of flanking asymmetric basins of sedimentation. Fault throws were implied to have been equivalent resulting in supra-horst sedimentation packages of similar thickness, both parallel and perpendicular to the rift axis.

New analysis of core, particularly depth constraints associated principally with Oronto strata and pre-Oronto age volcanic rock, permits the portrayal of the Midcontinent rift trend as a series of sub-basins separated by "accommodation zones." Three identified sub-basins are believed to have developed independently in the study area in response to rift stress and fault movements of contrasting magnitude. This resulted in sedimentation isopach polarities that are symmetric parallel, but asymmetric perpendicular, to the rift axis. From west to east these polarity orientations are south in Bayfield County, Wisconsin (Brule Basin), north onshore and offshore Ontonagon, Michigan (Ontonagon Basin), and south offshore Marquette, Michigan (Manitou Basin). A fourth basin (Cariboo Basin) is located southeast of the Manitou Basin, but is poorly defined from geologic and geophysical constraints. The accommodation zones are generally situated within the region of fluctuating sedimentation patterns and are specifically identified by offsetting Bouguer gravity patterns.

Although this Middle Proterozoic model may not be representative of the entire 20 to 40 m.y. developmental history of the entire length of the Midcontinent Rift System, it does encourage development of new models pertinent to rift evolution and the discovery of associated base-metal and hydrocarbon resources.

COMPARISON EAST AFRICAN AND MIDCONTINENT RIFT ELEMENTS¹

ELEMENT	AFRICAN MODEL	U.S. MODEL
SYSTEM	EAST AFRICAN RIFT	MIDCONTINENT RIFT
BRANCH	EASTERN WESTERN	MID-MICHIGAN GRAVITY HIGH ² MID-CONTINENT GRAVITY HIGH ²
ZONE 500-700 km in length	GREGORY (KENYA) STEFANIE (CHOW BAHIR) TANGANYIKA USNO-OMO-KIBISH	LAKE SUPERIOR ³ CENTRAL IOWA ³ NORTHEASTERN KANSAS ³ SOUTHERN MICHIGAN ³
UNIT ⁴ 80-160 km in length L/W ratio 2-4/1	TURKANA SUGATA BARINGO-BOGORIA ⁵ NAKURA-NAIVASHA ⁵ MAGADI-NATRON ⁵	MANITOU ONTONAGON BRULE CARIBOU
BLOCK ⁶ width 10 km L/W ratio 4-10/1	RECOGNIZED	RECOGNIZED

¹After rift Scale classification by Rosendahl (1987). The architectural elements should be considered typical, rather than correlative, examples.

²Known principally as geophysical entity

³After Dickas (1986)

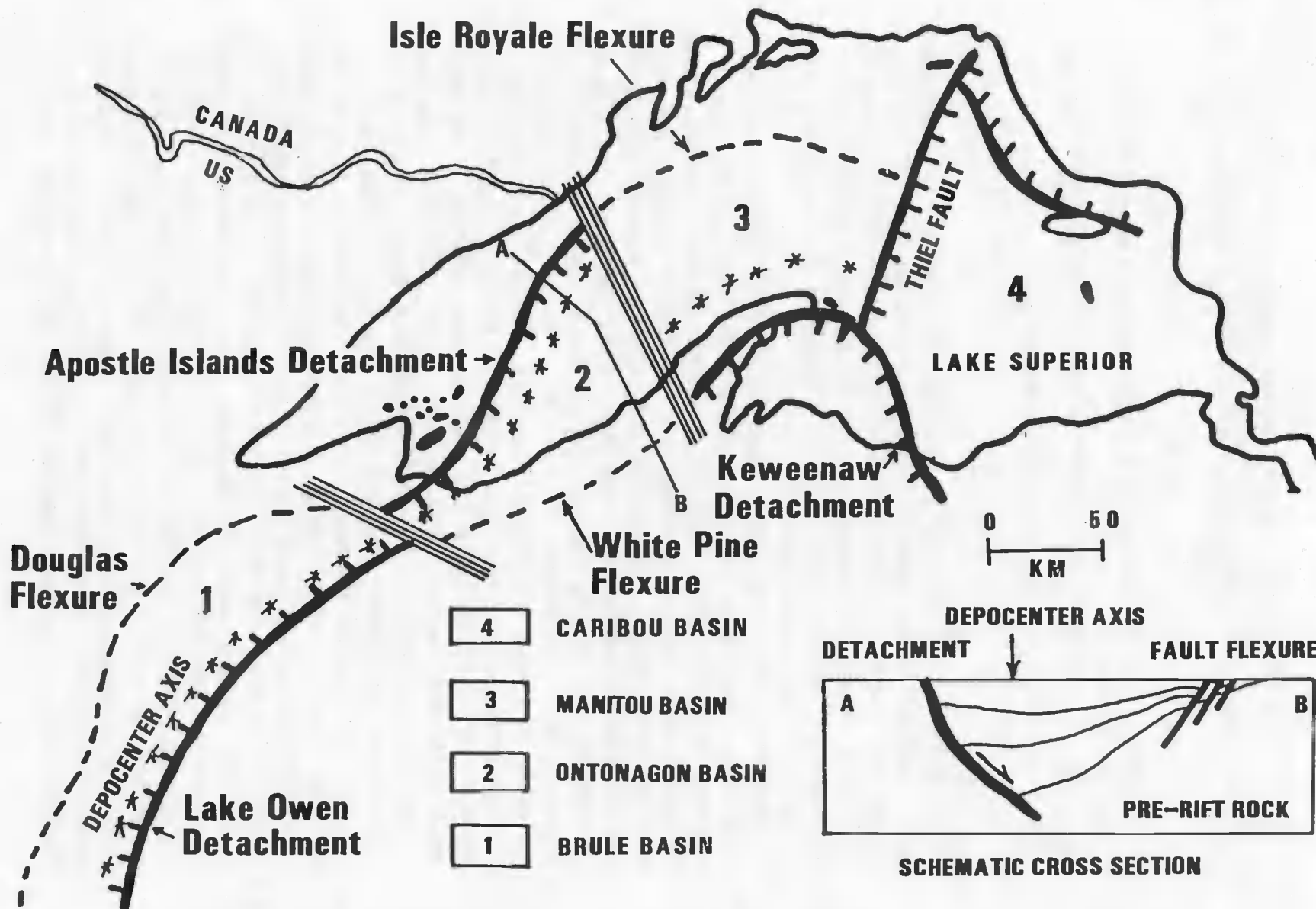
⁴Fundamental rift building block

⁵After Bosworth, Lambiase and Keisler (1986)

⁶Infrastructure of rift units

References Cited:

- Bosworth, William, Lambiase, Joseph, and Keisler, Ron, 1986, A new look at Gregory's Rift: The structural style of continental rifting: EOS, v. 67, no. 29, p. 577-582, 583.
- Dickas, A.B., 1986, Seismologic analysis of arrested stage development of the Midcontinent Rift: Geoscience Wisconsin, v. 11, p. 45-52.
- Rosendahl, B.R., 1987, Architecture of continental rifts with special reference to East Africa: Annual Reviews of Earth and Planetary Science, v. 15, p. 445-503.



WESTERN LAKE SUPERIOR STRUCTURE

**DEVELOPMENT OF THE MIDCONTINENT RIFT
IN THE LAKE SUPERIOR REGION:
PETROLOGIC AND GEOCHEMICAL CONSTRAINTS FOR A TECTONIC MODEL**

S.W. Nicholson, Dept. of Geology, University of Minnesota, Minneapolis, Minnesota 55455 and the U.S. Geological Survey, MS 954, Reston, Va. 22092

J.B. Paces, Dept. of Geology and Geological Engineering, Michigan Technological University, Houghton, Michigan 49931

W.F. Cannon, U.S. Geological Survey, MS 911, Reston, Va. 22092

Integration of new geochemical and isotopic data with new geophysical and geochronological data for western Lake Superior provides an excellent opportunity to develop a tectonic and magmatic model for the evolution of the Midcontinent rift. Basalt compositions became more primitive as the rift evolved, which suggests that the extent of crustal attenuation influenced the composition of the volcanic rocks that were erupted.

As the Midcontinent rift evolved, basaltic rocks exhibited a broad variation in composition, ranging from olivine through quartz tholeiites [1,2]. This discussion will focus on the North Shore volcanic group in Minnesota and the Portage Lake volcanic group in Michigan for which the most complete chemical and isotopic data have been compiled. The older North Shore basalts generally display more chemically evolved compositions ($Mg\# \approx 40-55$), showing enrichment in incompatible trace elements [1,3]. Younger basalts, including most of the Portage Lake volcanic group [5] and some of the North Shore basalts [1,2], are less-evolved olivine tholeiites ($Mg\# \approx 65-70$ and high compatible trace-element abundances). The most primitive tholeiites occur at the top of the Portage Lake section and represent the youngest flood basalts in the rift. Chemical variations among basalts can be attributed largely to crystal fractionation in subcrustal to intracrustal magma chambers, which were subject to replenishment, periodic tapping, crustal contamination, and minor variations in parent magma composition [4,5].

Nearly one hundred Nd isotopic analyses have been obtained for rocks from the North Shore [3,6] and the Portage Lake [5,7] volcanic groups. Despite chemical variations among the basalts, the ϵ_{Nd} values at 1100 Ma cluster about 0 (Fig. 1) [3,6,8,9]. The range of values for basalts from the North Shore is from about -9 to +3.5 [3,6], whereas basalts from the Portage Lake group show a more narrow range of values, from about -2 to +1.4 [5,7]. However, the strong clustering of values around 0 implies that most of the basalts in the western Lake Superior region were derived from a similar mantle source. The wide range in enriched isotopic compositions for North Shore basalts suggests some crustal contamination [10]. The more restricted composition of the Portage Lake basalts suggests less involvement of a crustal component. Within the Portage Lake group, the

amount of crustal component decreases upsection and virtually disappears during the latest stages of rifting [5]. Strongly enriched ϵ_{Nd} values at 1100 Ma of -13 to -16 obtained for some rhyolites in the North Shore and the Portage Lake areas [6,8] indicate that partial melting of Archean crust did occur locally. However, most rhyolites show isotopic compositions similar to those of the basalts, which suggests derivation from a similar source to that of the basalts [8].

In western Lake Superior, GLIMPCE seismic reflection profiles suggest that the main depositional basin of the rift was confined between two major faults, the Isle Royale-Douglas Fault on the north and the Keweenaw-Lake Owen Fault on the south. In this area, subsidence along the rift axis accommodated up to 30 km of rift-related volcanics and sediments. The Portage Lake volcanic group in Michigan, which are the youngest rift-related flood basalts, lies within this major depositional basin. However, the North Shore volcanic group in Minnesota lies within a broad shallow basin (about 5 km deep) to the northwest of the Isle Royale-Douglas Fault. This shallow basin probably developed during the early stages of rifting (reverse-polarity volcanic rocks occur at the base of the North Shore group), but was active at least until major subsidence occurred along the rift axis. Hence, the North Shore and Portage Lake volcanic groups were not emplaced in the same structural setting.

Integration of these data leads to the following model: In the early stages of rifting, thick continental crust impeded the rapid ascent of basaltic magma and permitted magma interaction with wallrock. Early basalts preserve chemical and isotopic evidence of fractional crystallization and crustal assimilation enroute to the surface. As the crust thinned during continued plate extension, magma conduits became established, and magmas that ascended more rapidly had less opportunity for crustal interaction. Younger basalts show more primitive compositions and less chemical or isotopic evidence of crustal contamination. The basin in which the North Shore group resides is underlain by continental crust which was thinned no more than a few kilometers, according to GLIMPCE data; compositions of the North Shore volcanic rocks reflect some crustal contamination. In contrast, the Portage Lake group lies at the edge of the major depositional basin beneath which the crust was greatly thinned or perhaps completely separated and replaced by sheeted dikes and sills [11]. The compositions of the youngest and most primitive basalts of the Portage Lake Volcanics suggest little or no interaction between basaltic magma and the continental crust in which the rift developed. Thus, the variation in the chemical characteristics of the volcanic rocks can be used to qualitatively infer the extent of crustal attenuation.

REFERENCES

1. Green, J.C., 1982, Geology of Keweenaw extrusive rocks, in R.J. Wold and W.J. Hinze, ed., *Geology and tectonics of the Lake Superior Basin*: Geological Society of America, Memoir 156, p. 47-55.
2. Basaltic Volcanism Study Project, 1981, Pre-Tertiary continental flood basalts, in *Basaltic volcanism on the terrestrial planets*: Pergamon Press, p. 30-77.
3. Brannon, J.C., 1984, Geochemistry of successive lava flows of the Keweenaw North Shore Volcanic Group: Washington University, St. Louis, Missouri, Ph.D. dissertation, 312 pp.
4. Miller, J.D., 1987, The geology and petrology of anorthositic rocks in the Duluth complex, Snowbank Lake quadrangle, northeastern Minnesota: University of Minnesota, Minneapolis, Minnesota, Ph.D. dissertation, 436 pp.
5. Paces, J.B., 1988, Geochemical and isotopic evaluation of the magmatic processes, evolution and mantle source involved in development of the major Keweenaw continental flood basalt basin: Portage Lake Volcanics, Keweenaw Peninsula, Michigan: Michigan Technological University, Houghton, Michigan, Ph.D. dissertation
6. Dosso, L., 1984, The nature of the Precambrian subcontinental mantle: isotopic study (Sr, Pb, Nd) of the Keweenaw volcanism of the North Shore of Lake Superior: University of Minnesota, Minneapolis, Minnesota, Ph.D. dissertation, 221 pp.
7. Nicholson (in prep)
8. Nicholson, S.W. and Shirey, S.B., 1987, 1100-Ma midcontinent rift development: evidence from Nd and Sr isotopic composition of Keweenaw volcanic rocks, northern Michigan: Geological Society of America, Abstracts with Program, v. 19, p. 788.
9. Paces, J.B. and Bell, K., (in review), Enriched shallow lithospheric mantle beneath the Superior Province: Nd-Sr isotopic evidence from uncontaminated 1.1 Ga midcontinent rift olivine tholeiites, Keweenaw Peninsula, Michigan: submitted to *Geochimica et Cosmochimica Acta*
10. Dosso, L., 1985, The nature of the Precambrian subcontinental mantle: isotopic data (Sr, Nd, Pb) on the Keweenaw volcanism of the North Shore of Lake Superior: (abst.), *Terra Cognita*, v.5, p. 207.
11. Behrendt, J.C., Green, A.C., Cannon, W.F., Hutchinson, D.R., Lee, M.W., Milkereit, B., Agena, W.F. and Spencer, C., 1988, Crustal structure of the Midcontinent rift system: results from GLIMPCE deep seismic reflection profiles: *Geology*, v. 16, p. 81-85.

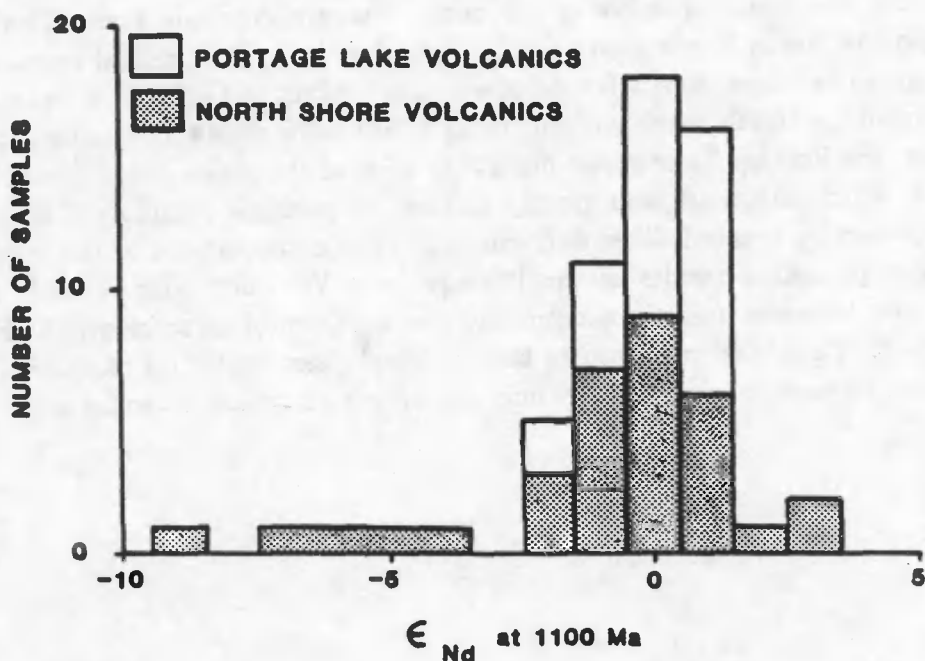


Fig. 1: ϵ_{Nd} values at 1100 Ma cluster around 0 for volcanic rocks in both the Portage Lake and North Shore volcanic groups with $< \sim 56\% \text{ SiO}_2$.

THE KEWEENAWAN RIFT: A KINEMATIC MODEL FOR ITS ORIGIN AND EVOLUTION

Peter A. Nielsen, Department of Geology, UW-Parkside, Kenosha, WI 53141

The Midcontinent Rift System (MCRS) has been modelled as a passive structure, or impactogen, caused by the Grenville Orogeny and as an active, or plume induced structure. I show, that based on an analysis of the stress conditions present in the North American Plate (NAP) from ~ 1400-1000 Ma b.p., the MCRS was an active rrr triple junction. Global plate distribution could not accomodate unconfined extension of the NAP and this prevented the MCRS from proceeding to sea-floor spreading (Figure 1).

The MCRS is unique in that there is no classical third arm associated with it. However, the Coldwell Trend, a series of 1130-1110 Ma alkaline intrusive centers may represent the location of the third arm.

Stress distribution was primarily a function of the nature of the North American Plate's continental margin types as well as the types of plate boundaries present. The NAP was characterized by passive continental margins in the west and north and by an active continental convergent margin in the east. Plate boundaries, therefore, were mid-ocean ridges in the west and north and a convergent boundary in the east and southeast. These boundary conditions produced a stress field that was dominantly inward directed compression, comprised of west and northwest, directed compression at its eastern margin (the site of the Grenville Orogeny), eastward directed compression at the western, passive, continent-ocean margin (site of Belt Group and equivalent sedimentation), and possibly southward directed compression along the northern margin (the site of a 1200 Ma rifting center). The absence of an oceanic free face by 1160 Ma (ocean-continent or ocean-ocean convergent margin) bounding the NAP coupled with the net compressive stress fields effectively pinned the NAP, limited rifting to 65-70 km, prevented the MCRS from proceeding to mid-ocean ridge status and precluded the active stage of rifting along the arm defined by the Coldwell trend.

The system of gravity and magnetic anomalies that extends from Kansas to Lake Superior and then southwards into central Michigan and into eastern Ohio is one of the most prominent in North America. It reflects a major geologic event which has been identified as an abortive rifting of the North American craton - the MCRS, summarized in Wold & Hinze, 1982. Numerous authors have proposed that this feature is a result of active rifting processes in response to one or more hot spots intersecting the North American Plate approximately 1250 to 1100 Ma b.p. (Burke & Dewey, 1973; van Schmus & Hinze, 1985). Others (Tapponnier et al., 1982; Gordon & Hempton, 1986) have presented arguments that the tensional environment represented by the MCRS may have resulted from the Grenville Orogenic event.

The petrology and geochemistry of the Keweenawan igneous rocks, as exposed in the Lake Superior region, require that: 1) multiple source regions contributed magma; 2) partial melting occurred over a range of depths; and 3) one or more of the sources was REE undepleted.

Three magma series were proposed by Weiblen (1982). They were: 1) alkaline (CO_2 -rich to CO_2 -poor), 2) quartz tholeiite (alkalic, high Ti), and

3) olivine-tholeiite (low alkali, high Al). The first two series have REE patterns and initial Sr ratios compatible with derivation from a mantle plume source (Weiblen, 1982; Wilband, 1985). The olivine tholeiites have REE patterns and bulk compositions which correspond closely to mid-ocean ridge basalts (Weiblen, 1982).

The order of emplacement of the three magma series and the transition from REE undepleted, plume derived melts to MORB type melts strongly supports the hypothesis that the MCRS formed as an active rift system.

Recent and current research in the best exposed Grenville rocks (Brown et al., 1986; Easton, 1986; Windley, 1986, summarized in Moore et al. 1986) constrain stress distribution along a region parallel to the strike of the Coldwell Trend, and indicate that by 1160 Ma b.p. NW directed thrusting was prominent. Davidson (personal communication, 1987) suggests that these major NW compressional shear zones represent thrust stacking activity that shifted SE with time due to locking up and stepping back of Benioff zones. Any sutures associated with this activity are now cryptic. The timing of this NW directed stress parallel to the Coldwell Trend and the Grenville Front provide the necessary stress field to prevent any rifting along this possible third rift arm. The absence of any rift-type cracking along the Coldwell trend strongly argues against a passive origin for the MCRS, for it is in the region parallel to crustal thickening, that crustal flexure and failure should occur.

The absence of any controls on the distribution of Central Metasedimentary Belt age rocks south of the Adirondacks, their spotty distribution in northern Quebec and absence in Newfoundland (Figure 2, Easton, 1986), coupled with the apparent truncation of the SE trending arm of the MCRS in the vicinity of the west end of Lake Erie, and the change in orientation of the Grenville Front south of Lake Erie strongly argue that the MCRS is not passive in origin.

CONCLUSIONS

The Midcontinent Rift System was an active, plume induced rrr triple junction. Near constant stress magnitude and orientation from the western and northern margins of the North American Plate coupled with changing stress conditions on the eastern margin prevented the arm defined by the Coldwell Trend from rifting or producing mafic volcanics. Evolving stress conditions later stopped further rifting on the Michigan segment and finally along the Lake Superior segment. The MCRS and the Grenville Orogeny overlapped in time, but there was no genetic relationship between the two. The only effect of the Grenville Orogeny was to cause the failure of the MCRS to proceed to sea-floor spreading.

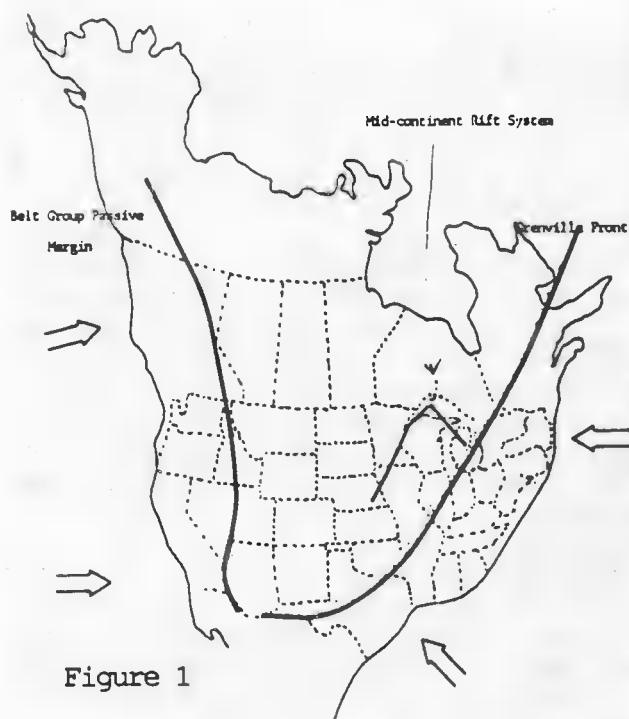


Figure 1

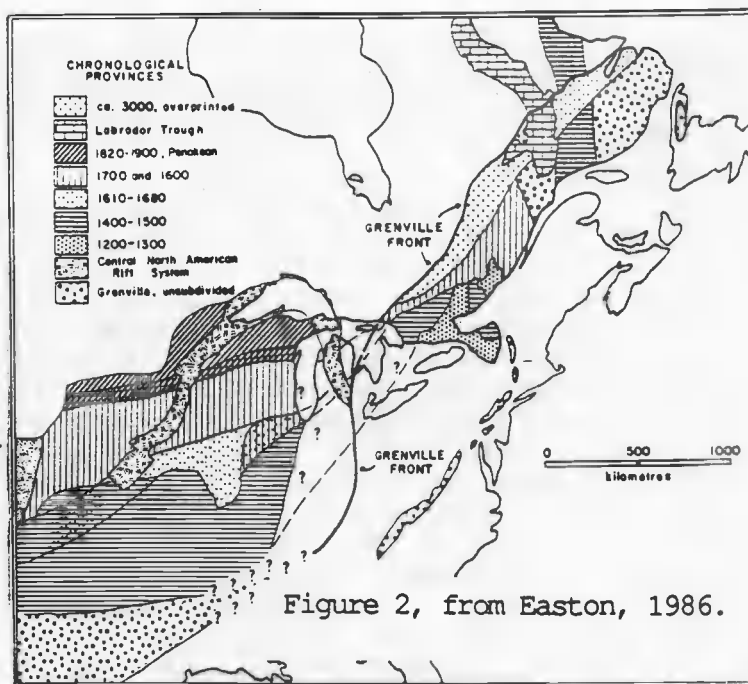


Figure 2, from Easton, 1986.

BIBLIOGRAPHY

- Brown, R.L., Chappel, J.F., Moore, J.M., and Thompson, P.H., 1975, An enigmatic island arc and ocean closure in the Grenville Province of southeastern Ontario, Canada, *Geoscience Canada*, v. 2, pp. 141-144
- Burke, K.C.A., and Dewey, J.F., 1973 Plume generated triple junctions: Key indicators in applying plate tectonics to old rocks, *Journal of Geology*, v. 86, pp. 406-433
- Easton, R.M., 1986, Geochronology of the Grenville Province, in Moore, J.M., Davidson, A., and Baer, A.J., eds. *The Grenville Province, Geological Association of Canada Special Paper 31*, pp. 127-173
- Gordon, M.B., and Hempton, M.R., 1986, Collision-induced rifting: The Grenville Orogeny and the Keweenaw Rift of North America, *Tectonophysics*, v. 127, pp.1-25
- Moore, J.M., Davidson, A., and Baer, A.J., editors, 1986, *The Grenville Province, Geological Association of Canada Special Paper 31*, 358 pp
- Van Schmus, W.R., and Hinze, W.J., 1985, The midcontinent rift system, *Annual Reviews of the Earth and Planetary Sciences*, v. 13, pp. 345-383
- Wieblen, P.W., 1982, Keweenaw intrusive rocks, 1982 in Wold, R.J., and Hinze, W.J., editors, 1982, *Geology and Tectonics of the Lake Superior Basin, Geological Society of America Memoir 156* 280 pp., pp. 47-56
- Wilband, J.T., 1985, Magmatic processes during the Midcontinent Rift interval in northeastern Michigan: Chemical and isotopic constraints, *Proceedings of the Annual Institute on Lake Superior Geology*, v.31,p.97
- Windley, B.F., 1986, Comparative Tectonics of the Western Grenville and the Western Himalaya, in Moore, J.M., Davidson, A., and Baer, A.J., eds. *The Grenville Province, Geological Association of Canada Special Paper 31*, pp. 341-348
- Wold, R.J., and Hinze, W.J., editors, 1982, *Geology and Tectonics of the Lake Superior Basin, Geological Society of America Memoir 156* 280 pp.

History of Precious Metal Exploration/Development
in the Dead River - Ishpeming Greenstone Belt

JOHN W. NORBY (Callahan Mining Corporation, Exploration Dept,
25 Industrial Park, Negaunee, MI 49866)

The Dead River - Ishpeming Greenstone Belt (DIGB) is located in northern Marquette County, Michigan and is part of the Archean Superior Province. Gold was first discovered in the DIGB by Douglass Houghton, Michigan's first State geologist (1837-1845), who panned the metal from an undisclosed location between L'Anse and Marquette. In the mid-1860s base metal - silver veins in the middle DIGB were worked for their lead, needed in the production of minie balls used by Federal armies fighting the Civil War, and for their silver credits.

In 1880, Julius Ropes discovered the mine that was to bear his name in the southwest DIGB. From 1882 to 1897 the Ropes Gold Mine produced 41,280 oz Au and 193,500 oz Ag. Two other mines have recorded production from this era: the Michigan Mine (875 oz) in the southwest DIGB, and the Fire Center Mine (97 oz) in the middle DIGB. Numerous additional prospects in the southwest DIGB were developed in the late 1880s and worked sporadically until the 1893 depression. At the turn of the century, cyanidization of Ropes tails and mill amalgam netted 2,645 oz Au.

In 1934, the 69% rise in gold price to \$35 US stimulated renewed activity. From that year through 1942 Calumet and Hecla Consolidated Copper Co. developed 1mT grading 0.13 oz/ton Au, 0.7 oz/ton Ag in the Ropes Gold Mine. In 1936, Norgan Gold Mining Co. conducted a reconnaissance program throughout the belt, culminating in a 13-hole drill test of the Fire Center trend. The 1942 War Powers Act halted the development of US gold properties.

During the 1960s and 70s, the DIGB was the subject of massive sulfide exploration, but much of the generated core was assayed for precious metals, providing information to later gold prospectors. Callahan Mining Corp. purchased the Ropes Gold Mine in 1975. After the US abandonment of the gold standard in 1973 and subsequent rise in price of that commodity throughout the decade, exploration in the belt switched to gold in the early 1980s. In 1983, Callahan made the decision to mine the Ropes orebody, and production commenced in September 1985. The Ropes Gold Mine had produced 83,671 oz Au and 113,014 oz Ag through the third quarter of 1987, bringing total precious metal production in the DIGB to approximately 128,500 oz Au and 306,500 oz Ag.

CHRONOLOGY

Precious Metal Exploration/Development Dead River - Ishpeming Greenstone Belt (DIGB)

- 1837 - 1845 Douglass Houghton discovers placer gold at unrecorded location between L'Anse and Marquette.
- mid 1860s Base metal - silver veins in middle DIGB worked, including Silver Creek prospect (4 shallow shafts), Silver Lakes mines (2 shafts, adit, winze), Lead pits.
- 1864 - 1865 Holyoke precious and base metal mine developed (526 ft adit, 64 ft winze), no production.
- 1880 Julius Ropes discovers gold west of Deer Lake.
- 1882 - 1897 Ropes Gold and Silver Co. produces 215,000 tons at 0.192 oz/ton Au, 0.90 oz/ton Ag from Ropes Mine.
- late 1880s East-west quartz vein trend in extreme southwest DIGB explored. Prospects include Lake Superior Gold, Lake Superior Iron, Superior, Breitung, Grayling, and Mockler Brothers, plus Michigan Mine. Nearby Peninsula prospect also worked.
- 1887 - 1894 Michigan Mine in operation (2,065 ft of workings), produces 3,500 tons at 0.25 oz/ton Au.
- 1891 - 1893 Fire Center Mining Co. produces 225 tons at 0.43 oz/ton Au from Beaver shafts and Crescent tunnel.
- 1899 - 1901 Corrigan, McKinney and Co. treat Ropes tails, 30,000 tons & mill amalgam yield 2,645 eqv oz Au.
- 1932 Yellow Dog Plains glacial drift gold explored, surface bulk samples, 6 drill holes (500 ft).
- 1934 Michigan Mine dewatered by Marquette Mines Co., 500 tons milled, no recorded production.
- 1934 - 1942 Calumet and Hecla Consolidated Copper Co. evaluates Ropes Gold Mine, 2,550 ft underground development, 94 underground drill holes (10,885 ft). At surface, drills 6 holes on property (1,564 ft), 3 holes east of Ropes (1,278 ft), 8 holes west of Ropes (4,109 ft), and 5 holes at Bjork-Lundeen prospect (2,109 ft).
- 1936 Norgan Gold Mining Co. prospects entire DIGB, drills 13 holes (1,999 ft) along Fire Center trend.

CHRONOLOGY - DIGB Precious Metals Exploration/Development, cont.

- 1966 The Cleveland-Cliffs Iron Company (CCI) drill tests Michigan Mine, 3 holes.
- 1968 - 1971 Humble Oil (later Exxon) explores middle and southwest DIGB for massive sulfide, analyzes for precious metals. Drills 2 holes into iron formation and 2 into topographic low (2,000 ft).
- 1970s Beth-Cliffs JV (Bethlehem Steel and CCI).
- 1975 Resource Exploration, Inc. (REI) presents Ropes Gold Mine data to Callahan Mining Corp. which purchases property from Arcadian Copper Mine Tours (owner since 1955).
- 1972 - 1985 Superior Oil Co. and Nicor Mineral Ventures JV prospects middle and northwest DIGB for massive sulfide, several geophysical and/or geochemical anomalies drilled, REI project manager thru 1983. Emphasis switches to gold that year, several additional targets drilled. During both phases of exploration JV drills 14 holes (4,700 ft) on Holyoke property.
- 1977 - 1981 NOMEX AU JV (Chevron and CCI) explores southwest DIGB, drills 4 holes at Bjork-Lundeen prospect (2,729 ft) and 4 holes west of Ropes (1,680 ft).
- 1979 - 1981 Callahan evaluates Ropes Gold Mine, REI project manager. Drills 18 surface holes (12,724 ft) into orebody and 2 into IP anomaly (802 ft), plus 8,000 ft of underground drilling.
- 1984 - psnt Kerr-McGee Corp prospects middle DIGB, actively drilling.
- 1983 St. Joe American Corp. prospects patchwork of land in northern and southern DIGB, no holes drilled.
- 1983 - 1985 Callahan makes production decision, develops Ropes Gold Mine to 900 ft level. Acquires and renovates iron ore flotation mill in Champion.
- 1984 - psnt Callahan prospects for additional reserves on Ropes property and in other areas within hauling radius of Ropes mill, actively drilling.
- 1985 - 1986 Phelps Dodge prospects southwest DIGB, drills 1 hole east of Ropes (824 ft).
- 9/85 - 9/87 Callahan mills 1.25 mT at 0.087 oz/ton Au, 0.28 oz/ton Ag from Ropes orebody above 1284 ft level.

IMPLICATIONS OF HIGH PRECISION U-Pb AGE DATES ON ZIRCONS FROM PORTAGE LAKE VOLCANIC BASALTS ON MIDCONTINENT RIFT SUBSIDENCE RATES, LAVA FLOW REPOSE PERIODS AND MAGMA PRODUCTION RATES

JAMES B. PACES, Dept. Geology & Geological Engrg.,
Michigan Technological University, Houghton, MI 49931

DON W. DAVIS, Jack Satterly Geochronology Laboratory,
Royal Ontario Museum, 100 Queen's Park, Toronto, Ontario M5S 2C6

Recent high precision U-Pb zircon dating of Keweenaw-aged rocks in the western Lake Superior region has revealed that basaltic igneous activity associated with the Midcontinent Rift (MCR) was initiated around 1109 Ma¹. Dates of similar quality which record the cessation of extensive flood basalt extrusion do not exist. In this paper, we report new dates which constrain the upper age limit of MCR mafic volcanism, and use these data to estimate rates of rift-related tectonic and igneous processes.

STRATIGRAPHY

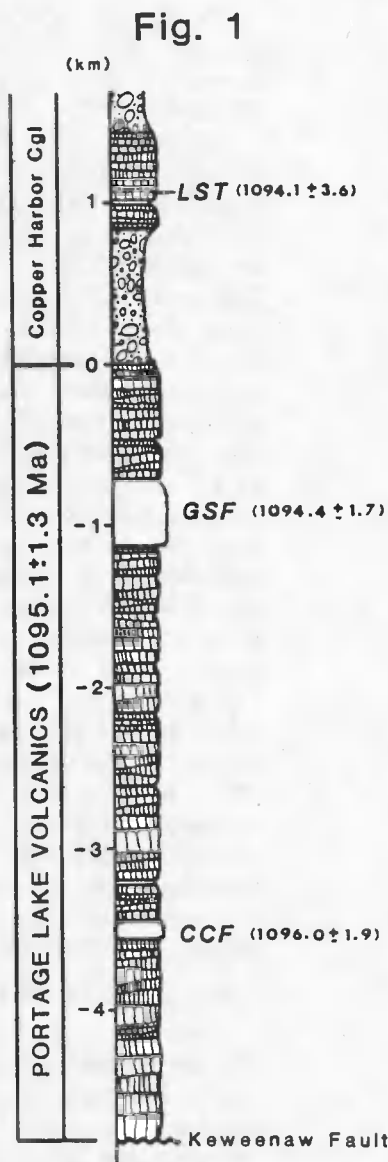
The Portage Lake Volcanics (PLV), northwest Michigan, represents the youngest flood basalt-filled portion of the MCR in the western Lake Superior region². The thick pile (3-5 km) of normal magnetic polarity, predominantly olivine tholeiite lavas is conformably overlain by Oronto Group sediments. This sequence of rocks therefore records a major transition in MCR evolution from dominantly volcanic to sedimentary rift-filling material.

Figure 1 shows generalized stratigraphic relationships in the Keweenaw Peninsula. Highly differentiated pegmatoid layers within two PLV flows, the Greenstone Flow and Copper City Flow (GSF and CCF respectively), were sampled for zircon extraction. The stratigraphic horizons represented by these flows are separated by 2600-3100 m of flood basalts and minor interflow sediments. A single lava from a series of flows (Lake Shore Traps, LST) within the Copper Harbor Conglomerate was also sampled. LST magmatism is separated from the GSF horizon by approximately 700 m of PLV lavas and 800-1000 m of coarse clastic sediment.

RESULTS

Ages were determined from U-Pb data on multiple fractions of abraded zircon separates. All data points plot close to the concordia curve suggesting that problems of lead loss and inheritance are minimal. Six zircon fractions from the two PLV samples and two fractions from the LST sample yield ages of 1095.1 ± 1.3 Ma and 1094.1 ± 3.6 Ma respectively (based on zero age lower intercepts; errors on all data are quoted at 95% confidence levels). PLV and LST ages are unresolvable from the present data. Within the PLV section, separate ages for the GSF and CCF horizons are 1094.4 ± 1.7 Ma and 1096.0 ± 1.9 Ma respectively. The GSF-CCF age difference and one sigma error is 1.6 ± 1.3 Ma.

The age reported for the PLV is consistent with slightly older, reverse magnetic polarity lavas from the Black Bay Peninsula (upper Osler Group, 1097.6 ± 3.7 Ma¹). These age



relationships suggest that all of the normal polarity flood basalts associated with the western Lake Superior segment of the MCR were produced over a period of 2-3 Ma. However, an age reported from a porphyritic intrusive/subintrusive unit on Michipicoten Island ($1086.5 \pm 1.3/-3.0$ Ma³) is significantly younger than PLV or LST ages reported here. This large age difference implies that either 1) volcanic rocks in the eastern MCR are much younger than those to the west, 2) the Michipicoten Island Formation represents a much later, isolated magmatic episode, or 3) intrusion occurred much later than deposition of the volcanic host rocks.

RATES OF SUBSIDENCE

Combined geochronologic and stratigraphic data can be used to estimate minimum rates of rift-related subsidence. The assumption underlying this calculation, maintenance of a near horizontal depositional surface, is supported by flow morphology, primary slope variations⁴, and distributions of interflow sediments. An average thickness of 2850 m between the GSF and CCF horizons and the age difference of 1.6-1.9 Ma yields subsidence rates of 1.5 to 2.0 mm/yr. Although higher rates may occur along the MCR axis, the values calculated from GSF-CCF data are comparable with rates of tectonic subsidence in other continental grabens (typically 1-2 mm/yr; range of 0.2-10 mm/yr). The large error in the reported LST age reduces the significance of similarly calculated rates for the GSF-LST interval. PLV subsidence rates are roughly an order of magnitude greater than those calculated from Osler Group data (0.12-0.24 mm/yr). However, 1.5-2 mm/yr subsidence over the 12-13 Ma period of MCR magmatic activity (1108-1095 Ma) would have resulted in the accumulation of 18-26 km of rift-fill. This thickness added to 8-10 km of overlying post-magmatic sediments^{5,6} yields total rift-fill values in close agreement with recent seismic reflection results⁷.

LAVA REPOSE PERIODICITY

Average interflow repose periods can also be estimated from the GSF-CCF data. Up to 140 separate cooling units are recognizable over this stratigraphic interval, however the presence of compound flows reduces this number to approximately 65-70

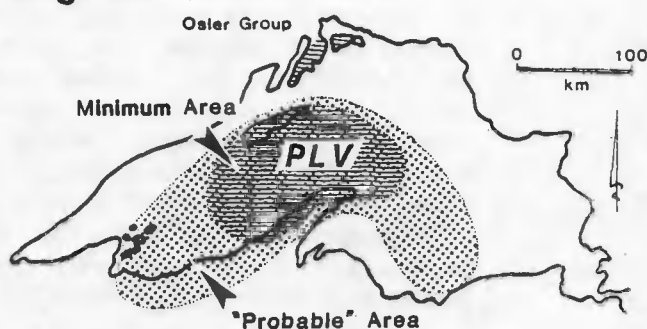
major lava flows. Therefore, the average repose period between successive major eruptions is estimated at 20-30 Ka. Somewhat longer repose may typify eruptions separated by interflow sedimentary units while shorter repose periods may be typical of the majority of PLV flows which directly overlay the underlying flow top.

RATES OF MAGMA PRODUCTION

Finally, minimum rates of magma production have been calculated for the CCF-GSF interval. Total volume of eruptive products is speculative given present exposure. Minimal and "probable" estimates of the original areal extent of PLV lavas are shown in Figure 2 (modified after Green⁸). Constant thickness across the basin is assumed (axial thickening is counteracted by marginal thinning). Estimates of minimal and "probable" volumes for the GSF-CCF interval are approximately 40,000 and 100,000 km³ respectively which result in magma production rates between $2-6 \times 10^{-2}$ km³/yr. Although these values may be underestimated by a factor of 2-5, they fall within the range of values estimated for basaltic magma production in other rift and hot spot settings (Iceland 5×10^{-2} km³/yr; Columbia River Basalts 7×10^{-2} km³/yr; and Hawaii $3-10 \times 10^{-2}$ km³/yr⁹).

- ¹ Davis and Sutcliffe (1986) GSA Bull 96: 1572. ² Green (1982) GSA Mem 156: 47. ³ Palmer and Davis (1987) Precambrian Res 37: 157. ⁴ White (1960) Am J Sci 258A: 367. ⁵ Daniels (1982) GSA Mem 156: 107. ⁶ Kallioowski (1982) GSA Mem 156: 147. ⁷ Behrendt (1988) Geology 16: 81. ⁸ Green (1983) Tectonophysics 94: 413. ⁹ Swanson et al. (1975) Am J Sci 275: 877.

Fig. 2



Archean and Proterozoic Tectonics - Northern Michigan A Speculative Synthesis

John C. Palmquist, Geology Department
Lawrence University, Appleton, WI 54912

These eclectic tectonic interpretations are offered as an attempt to call attention to the Archean ancestry of the Penokean orogeny and to reconcile the apparent conflicts in previously published ideas about the nature of the Penokean deformation (vertical vs. horizontal tectonics) and the contrasting views concerns the nature of basement-cover interaction (brittle basement blocks vs. ductile basement-cover relationships). Two sets of conflicting tectonic concepts have been presented in both the district and the region. One concerning the question of the role of the Archean basement behavior during the Penokean - was it ductile or brittle? The second conflict has to do with reconciliation of the steep fault zones and near vertical axial surfaces of folds and cleavages with the recumbent folding in adjacent areas.

Archean scenario. A southern gneissic terrane (southern complex) and northern greenstone-granitic terrane (northern complex) were juxtaposed in proto-continental collision to form the Great Lakes Tectonic Zone (GLTZ) of Sims, (1980). Dextral shear along the GLTZ may have created a series of low pressure zones which guided the emplacement of the Compeau Creek plutons into syntectonic relations with the greenstones of the northern complex and the gneiss of the southern complex. Strain patterns in the Archean greenstone belt of the Vermilion District, Minnesota have been shown by Schultz-Ela (1986) to indicate dextral transpression. A convincing example of a granite pluton emplaced in a pull-apart associated with the South American Shear Zone of France is given by Guineberteau and others, (1987). Diabase dikes of multiple ages were intruded along fractures and faults in both the northern and southern complexes as an accompaniment of regional uplift and/or "relaxation" of the syntectonic emplacement. Later remobilization of the complexes is indicated by the deformation patterns in the southern gneissic terrain and by dismembered and contorted remnants of early dikes in the northern complex. The remnants appear as diffused, feldspathized amphibolites and schlieren in the Compeau Creek gneiss. Some of these amphibolite "ghosts" may represent incomplete assimilation of Mona schist (Stonehouse, 1970).

Penokean orogeny. The rift destined to become the Marquette synclinorium began to close by transpression (Cambray, 1984) along the site of the GLTZ. A southward directed subduction zone somewhere under the present area of northern Wisconsin juxtaposed the Baraga, Menominee and Chocolay Groups in an accretionary wedge (Larue and Ueng, 1985). Underthrusting of the footwall caused the piling up of a wedge comprised of a series of thrusts, including the crystalline cored nappe preserved in the Felch District (Maharidge and others, 1986). As the thrust sheets advanced relatively northward (the footwall may have been actively subducting southward), toward the foreland, their leading edges may have been diverted into topographic lows, i.e., diverged around topographic buttresses, possibly the gneisses of the southern complex. Where the thrusts were thickly stacked, depressed geotherms formed the metamorphic nodes at

Watersmeet, Peavy and Republic (Attoh, 1986) following a thermal lag. The northward thinning of the tectonic load would have caused thermal weakness to slope up toward the foreland. The anisotropy in the Archean rocks averted the shortening direction and modified the transpressional tectonic trends to allow Penokean reactivation of Archean structures. Differential thermal weakening of diverse foreland (footwall) Archean rocks would allow some portions of the footwall to yield as brittle blocks whereas other portions, either initially weaker or more heated, would fail by folding, plastically flowing, or melting into the hanging wall rocks. Ellis (1988) explored the idea that thrusting migrates toward the foreland and that the footwall/foreland section will begin to deform internally by analyzing the strength of a rheologically simple two-layer lithosphere under compression.

This interpretation resolves the dilemma of the vertical axial surfaces seen at the east end of the Marquette synclinorium with the horizontal axial planes in the west. The evidence of a block-like behavior of the basement and the draping of the supracrustal rocks (Marquette and Republic - Klasner and Cannon, 1974) in seeming conflict with the indications of a ductile interaction of basement and cover (Watersmeet area) may also be resolved by the interpretation offered here - the basement (footwall) rocks were raised from a ductile environment through the ductile-brittle transition as the footwall/foreland deformed internally during the Penokean orogeny. At the east end of the Marquette synclinorium, ductile greenstones appear to have interacted with the metasedimentary rocks because basement and cover rocks have similar mechanical properties (Carter and Palmquist, 1986). Where stronger gneisses were uplifted en bloc the weaker, layered metasediments are draped over basement blocks in the fashion of the Rocky Mountain foreland uplifts associated with Laramide thrusting. In the Rockies, however, a more homogenous crystalline basement and a cooler thermal structure caused the basement rocks to behave in a more uniform, brittle, block-like fashion. In the Lake Superior region, the GLTZ of the Archean foreland created zones of weakness that localized the Marquette synclinorium and the Dead River Basin. Presumably, the vertical axial surfaces at the east end of the Marquette synclinorium and the horizontal axial surfaces on the west have resulted from the same north-south shortening event, the Penokean footwall/foreland compression. Recumbent isoclinal folds described by (Klasner, 1972) at the west end of the synclinorium might be interpreted as the spilling over of the Baraga Group as these rocks escaped the confinement of the footwall "jaws" and were flattened by gravitational force.

Where the tectonic loading has sufficiently heated the crust, basement gneisses have become ductile along with the metasedimentary rocks (Watersmeet node). Differential thermal and mechanical susceptibility in the basement rocks may have concentrated strain along ductile zones leaving intermediate areas unaffected and free to deform en bloc (Republic node). Thus, metamorphic conditions may locally reset radiometric clocks without penetratively deforming or remobilizing the basement everywhere during the Penokean metamorphic event.

REFERENCES

- Attoh, K. 1986, Metamorphic Pressures, Temperatures and Early Proterozoic Geotherms in Northern Michigan [Abstract], Thirty-second Ann. Inst. on Lake Superior geology, p. 5-6.
- Cambray, W.F., 1984, Proterozoic Geology, Lake Superior South Shore, Geological Association of Canada Field Trip Guide 5.
- Carter, P.J., and Palmquist, J.C., 1986, Strain Analysis of Deformed Archean Pillow Lavas, Mona Schist, Marquette County, Michigan, U.S.A. [Abstract]. Thirty-second Ann. Inst. on Lake Superior Geology, p. 16.
- Ellis, M., 1988, Lithospheric strength in compression: Initiation of subduction, flake tectonics, foreland migration of thrusting, and an origin of displaced terranes, *Journal of Geology*, v. 96, p. 91-100.
- Guineberteau, B., Bouchez, J. and Vignerresse, J., 1987, The Mortagne granite, pluton (France) emplaced by pull-apart along a shear zone: Structural and gravimetric arguments and regional implication, *Geological Society of America Bulletin*, v. 99, p. 763-770.
- Klasner, J.S., 1972, Style and sequence of a deformation and associated metamorphism due to the Penokean orogeny in the Western Marquette Range, northern Michigan [Ph.D. dissertation], Houghton, Michigan Technological University, 131 p.
- Klasner, J.S. and Cannon, W.F., 1974, Geologic Interpretation of Gravity Profiles in the Western Marquette District, Northern Michigan, *Geological Society of America Bulletin*, v. 85, p. 213-218.
- Larue, D.K. and Ueng, W.L., 1985, Florence-Niagara terrane: An early Proterozoic accretionary complex, Lake Superior region, U.S.A., *Geological Society of America Bulletin*, v. 96, p. 1179-1187.
- Maharidge, A.D., Mancuso, J.J. and Onasch, C.M., 1986, Tectonic Evolution of the Felch Trough [Abstract], thirty-second Ann. Inst. on Lake Superior geology, p. 53-54.
- Schultz-Ela, D., 1986, Strain Models for the Evolution of the Vermilion District, Minnesota [Abstract], Thirty-second Ann. Inst. on Lake Superior Geology, p. 71-72.
- Sims, P.K., 1980, Boundary between Archean Greenstone and Gneiss Terranes in Northern Wisconsin and Michigan, *Geological Society of America Special Paper* 182, p. 113-124.
- Stonehouse, H.B., 1970, Precambrian of the Marquette Area, Michigan, in *Guidebook for Field Trips*, Geological Society of America, North-Central Sec., Michigan Basin Geol. Soc., East Lansing, p. 159-177.

**Two generations of garnet growth in the Hardwood gneiss,
Dickinson County, Michigan**

J.W. PETERSON (Department of the Geophysical Sciences, University of Chicago, Chicago, IL 60637 U.S.A.)

C.A. OEIGER (Technische Universität Berlin, Institut für Mineralogie und Kristallographie, Ernst Reuter Platz 1, 1000 Berlin 12, West Germany)

The Hardwood gneiss is a unit of Early Precambrian age outcropping in eastern-central Dickinson County, Michigan. The general lithology of the unit was described by James et al., 1961* and consists of garnet-hornblende-pyroxene gneiss, plagioclase-quartz gneiss, hornblende-pyroxene gneiss, amphibolite, garnet-quartz-sillimanite-mica schist, and quartzite.

Two generations of garnet growth can be distinguished in the garnet-hornblende-pyroxene units. Generation I consists of subhedral to anhedral porphyroblasts of garnet, 1.0-2.5 mm in diameter, set in a fine-grained matrix of plagioclase and hornblende. Many of these garnets contain needles of rutile up to 100 μm long. Some garnets contain inclusions of cpx, opx, and plagioclase, though this is not common. Inclusion-free garnets have distinct rims. Generation II consists, in part, of distinct rims (80-100 μm wide) on the generation (I) garnets. These rims contain a band of irregularly-shaped oxide blebs (5-10 μm dimensions) which forms a sharp contact with the interior (generation I) portion of the garnet and a diffuse contact with the remainder of the garnet rim. Generation (II) garnet growth is also represented by 50-100 μm diameter euhedral garnets. These geometric grains are commonly cored with oxide blebs similar to those in the rims of generation (I) garnets. These cores are ~25 μm in diameter and consist of several individual oxide blebs ~5 μm in dimension. The euhedral garnets are commonly located around the rims of the larger generation (I) garnets. Because of the relative location of oxide blebs between the cores of euhedral garnets and the rims of sub-anhedral garnets, we infer that both rims and euhedral garnets grew contemporaneously, and at a distinctly different time than the generation (I) garnets.

In some samples, no large (generation I) garnets are present. However, augen-shaped areas (~1.5 mm by 1 mm) are present which contain 5-10 euhedral garnets, each 150-200 μm in diameter. These geometric garnets are rarely cored with oxides, but are riddled with inclusions of cpx, plagioclase, and hornblende. These augen may have been the locations of large generation (I) garnets which experienced later penetrative deformation and subsequently recrystallized to the small, euhedral generation (II) garnets. A difference in whole-rock bulk composition may explain the lack of oxide cores.

Electron microprobe analyses reveal compositional differences between the texturally defined generation (I) and (II) garnets. Quantitative thermobarometry indicates equilibration conditions of 850-950°C and 8-11 kbar for generation (I) garnets, and P-T conditions of 650-750°C and 7-8 kbar for generation (II) garnets.

The recognition of two generations of garnet growth at least records one portion of the decompression-cooling history for this high-grade terrane, and may discriminate between Archean and Proterozoic metamorphic events.

* James, H.L., Clark, L.D., Lamey, C.A. and Pettijohn, F.J., 1961, Geology of central Dickinson County Michigan: U.S. Geol. Survey Paper 310, 176 pp.

SULFIDE MINERALIZATION AND ASSOCIATED HYDROUS SILICATES IN ANORTHOSITIC ROCKS FROM THE DULUTH COMPLEX

Bernhardt Saini-Eidukat, Dept. of Geology and Geophysics,
University of Minnesota, Minneapolis, Minnesota 55455

The principal sulfide minerals in anorthositic rocks of the Duluth Complex, Minnesota, are chalcopyrite, pyrite and pentlandite. They occur as interstitial void-filling, included, and fine-veinlet textural types, similar to those observed in troctolitic series rocks (Weiblen and Morey, 1976).

Analyses of biotites in Duluth Complex anorthositic and troctolitic rocks show higher chlorine contents in biotites associated with sulfide mineralization. Substitution of chlorine (Cl) in biotite depends on temperature, Cl activity during equilibration, and the $Mg/(Mg+Fe)$ ratio ("mg") of the biotite (Munoz, 1984). Only the latter parameter is known in the case of the Duluth Complex. The expected correlation of increasing Cl with decreasing "mg" is observed (Table 1), but the highest Cl found also correlates with high sulfide content. At this point it is not known if the Cl content reflects dominantly a magmatic enrichment with differentiation, or the addition of Cl when S was added to the system (Ripley, 1981).

It has been proposed that Cl-complexing fluids may play an important role in the metallogenesis of platinum group element (PGE) deposits (Ballhaus and Stumpfl, 1986; Boudreau, Mathez and McCallum, 1986). Preliminary analyses of Duluth Complex rocks show a correlation of enrichment of chlorine with whole rock Cu, Ni and PGE enrichment. Although at this point in the investigation the role of Cl in metal concentration is equivocal, it is hoped that further study will provide exploration geologists with a tool for targeting PGE deposits in the Duluth Complex.

References:

- Ballhaus, C.G. and E.F. Stumpfl, 1986, Sulfide and platinum mineralization in the Merensky Reef: evidence from hydrous silicates and fluid inclusions. *Contr. Min. Pet.*, **94**, 193-204.
- Boudreau, A.E., Mathez, E.A. and I.S. McCallum, 1986, Halogen geochemistry of the Stillwater and Bushveld Complexes: evidence for transport of the platinum-group elements by Cl-rich fluids. *J. Petr.*, **27**, 967-986.
- Munoz, J.L., 1984, F-OH and Cl-OH exchange in micas with applications to hydrothermal ore deposits. In: Bailey, S.W. (ed.) *Micas*, Rev. Mineral. 13, Mineral. Soc. Am., Virginia, 469-494.
- Ripley, E.M., 1981, Sulfur isotopic studies of the Dunka Road Cu-Ni deposit, Duluth Complex, Minnesota. *Econ. Geol.*, **76**, 610-620.
- Weiblen, P.W. and G.B. Morey, 1976, Textural and compositional characteristics of sulfide ores from the basal contact zone of the South Kawishiwi intrusion, Duluth Complex, Northeastern Minnesota. *Proc. 37th Ann. Min. Symp.*, University of Minnesota.

	1	2	3
SiO ₂	32.48	34.45	37.87
TiO ₂	3.33	5.16	3.27
Al ₂ O ₃	14.41	13.93	16.55
Cr ₂ O ₃	0.19	0.04	0.06
FeO T	25.88	18.98	10.00
MgO	6.39	9.93	15.66
CaO	0.05	n.d.	0.09
Na ₂ O	0.33	0.37	0.42
K ₂ O	8.93	9.62	9.55
Cl	0.46	0.44	0.21
TOTAL	92.45	92.92	93.68
-O=Cl	92.35	92.82	93.63
Si	5.36	5.46	5.61
Ti	0.41	0.61	0.36
Al	2.80	2.60	2.89
Cr	0.02	0.01	0.01
Fe	3.57	2.51	1.24
Mg	1.57	2.34	3.46
Ca	0.01	n.d.	0.01
Na	0.11	0.11	0.12
K	1.88	1.94	1.81
Cl	0.13	0.12	0.05
TOTAL	15.87	15.71	15.56

Table 1. Analyses of biotites in Duluth Complex rocks.

n.d. = not detected. Numbers of ions on the basis of 22 O.

1. Troctolitic Series. INCO Test Pit sample 2B, Gabbro Lake Quad.
2. Anorthositic Series. Sulfide-bearing anorthosite. Gabbro Lake Quad., BL-27A-87
3. Anorthositic Series, late stage. Troctolitic anorthosite, sample 308A of Miller (Geology and Petrology of Anorthositic Rocks in the Duluth Complex, Snowbank Lake Quadrangle, Northeastern Minnesota. Ph.D. Thesis, 1986)

THE MAGNETIC FABRIC AND STRUCTURE OF THE QUETICO SLATES AT THE QUETICO-WABIGOON INTERFACE, NORTHWESTERN ONTARIO.

PERRY SARVAS and GRAHAM J. BORRADAILE. Department of Geology, Lakehead University, Thunder Bay, Ontario, Canada.

Recent studies of magnetic fabric in tectonites by many workers have repeatedly revealed a strong correlation between principal magnetic susceptibility directions and principal finite strain directions. These observations have led to this study of magnetic fabric in the Quetico slates to assist structural investigations.

The Archean Quetico metasedimentary belt, at the interface with the Wabigoon volcanic-plutonic subprovince, is characterized by sheath-folded greywacke-slate sequences of very low metamorphic grade. The sequences show a lateral metamorphic gradient towards the center of the Quetico subprovince, where migmatites are found. The sheath folds close to the belt boundary are primary, isoclinal and are believed to result from pervasive dextral transpression of the northern margin of the Quetico subprovince.

The Quetico metasedimentary rocks have a polyminerallic magnetic mineralogy, comprised of a small trace (<2 weight %) of highly magnetic grains (magnetite and pyrrhotite) and a much more substantial proportion of weakly magnetic minerals (phyllosilicates). Both fractions are believed to contribute significantly to both the magnetic susceptibility and the magnetic susceptibility anisotropy of the rocks.

The magnetic fabric of the Quetico slates is predominantly tectonic in derivation. The minimum magnetic susceptibility directions are consistently perpendicular to continuous cleavage planes. These cleavage planes parallel the major structural trends and metamorphic isograds, corresponding to the major episode of pervasive regional deformation/metamorphism. In places, a weak remnant sedimentological magnetic fabric is preserved.

The directions of maximum and intermediate magnetic susceptibilities vary throughout the area. This may be due to the influence of the phyllosilicates on the lithological magnetic susceptibility anisotropy (phyllosilicates have an oblate magnetic susceptibility ellipsoid, with poorly defined maximum and intermediate susceptibility directions). Also, the complexities introduced from a polyminerallic magnetic mineralogy, and a subordinate sedimentological magnetic fabric, could have influenced the orientations of the principal magnetic susceptibilities.

A Paleomagnetic Study of the Hamilton Mound
Area of Adams County, Central Wisconsin

Robert Schneiker
and
William F. Kean
Department of Geosciences
University of Wisconsin-Milwaukee
Milwaukee, WI 53201

The Hamilton Mound area represents a complex intrusion into precambrian quartzites. Magnetic measurements were made on the granitic intrusion, the complex mixed zone and the quartzites. The granite proved to be too magnetically viscous to provide reliable paleomagnetic directions. The magnetism in the quartzite appears to be caused by hematite, based on A.F. and thermal demagnetization studies. The pole position of the quartzite, after a correction for local structure is $N15^{\circ}$, $W120^{\circ}$, which is similar to the position for the Baraboo type quartzites of Wisconsin and Minnesota.

The mixed zone has a magnetism which is primarily carried by magnetite. The magnetic directions are well clustered and provide a pole position at $S20^{\circ}$, $W75^{\circ}$. This position probably represent the last age of intrusion at about 1600 m.y.a.

A POST-TECTONIC RARE-METAL-RICH GRANITE IN THE SOUTHERN COMPLEX, UPPER PENINSULA, MICHIGAN.

SCHULZ, K.J., U.S.Geological Survey, Reston, VA 22092; Sims, P.K. and Peterman, Z.E., U.S.Geological Survey, Denver, CO 80225.

We report herein preliminary results of a geochemical and Rb-Sr isotopic study of a small undeformed granite from the northern part of the Southern Complex, 2 miles south of Humboldt in the Upper Peninsula of Michigan. The granite, which is of probable Early Proterozoic age, is compositionally similar to rare-metal-rich granites and suggests a possible potential for Sn-W (Ta-Nb) mineralization in upper Michigan.

The granite, which was first discovered and briefly described by Hoffman (1987), is roughly circular in outline, about $1\frac{1}{2}$ miles in diameter, and intrudes the Archean Bell Creek granite and gneisses of the Southern Complex. The granite is generally massive, fine- to medium-grained equigranular to hypidiomorphic granular, nonfoliated, and light red to brick red. A prominent biotite foliation and(or) lineation is present locally near the margins. Fractures and joints are ubiquitous and typically are coated with micas. The mineralogy consists of K-feldspar, albite, quartz, biotite, muscovite, and accessory fluorite and zircon. Accessory uranothorite, columbite, euxenite, cassiterite, molybdenite, and topaz were reported by Hoffman (1987). According to the IUGS classification of plutonic rocks (Streckheisen, 1976), this body is an alkali-feldspar granite.

The granite is characterized by high SiO_2 (>74 %), low FeO_{T} (<2 %), MgO (<0.2 %), CaO (<0.5 %), and TiO_2 (<0.02 %), and near equal Na_2O and K_2O (4-5 %) contents. The trace elements Rb (350-1000 ppm), Pb (20-70 ppm), Y (28-115 ppm), Nb (35-209 ppm), and Ta (21-36 ppm) are strongly enriched, and Sr (<17 ppm), Ba (<20 ppm), and Eu (<0.07 ppm) are strongly depleted compared to average granites. The REE have U-shaped chondrite normalized patterns with very large negative Eu anomalies ($\text{Eu}/\text{Eu}^* < 0.025$).

Age determination by the Rb-Sr method on three whole rock samples defined a preliminary age of 1733^{+}_{-25} Ma and a Sr initial ratio of about $0.817^{+}_{-0.078}$ (Model I, MSWD = 1.55). Although this is a minimum age, it suggests that the granite may have been emplaced during the Early Proterozoic, perhaps contemporaneously with the ca. 1760 Ma anorogenic magmatism in Wisconsin. An Early Proterozoic post-Penokean age would be compatible with the lack of penetrative deformation and mineral alteration in this granite.

Compositional features of the granite stock are similar to those of Sn-W mineralized alkali-feldspar granites of the Arabian Shield (Jackson and Ramsay, 1986) and the Nigerian Younger Granite province (Kinnaird and others, 1985), and to the topaz rhyolite suite of the Western United States (Christiansen and others, 1986). Highly evolved, rare-metal-rich granite stocks, or cupolas, typically occur in clusters or linear arrays that commonly are related to larger granite bodies as, for example, in the Arabian Shield (Jackson and Ramsay, 1986). It is interesting to note that the granite near Humboldt lies on the

northeastern edge of a large negative gravity anomaly that is roughly coincident with the Republic metamorphic node; this anomaly has been attributed to a subjacent granite pluton (Klasner and others, 1985). Although highly greisenized rocks have not been found in the granite near Humboldt, its trace-element-enriched nature and the possible occurrence of other similar intrusions in the area suggests this region of the Upper Peninsula of Michigan may contain a significant potential for Sn-W (Ta-Nb) resources.

REFERENCES

- Christiansen, E.C., Sheridan, M.F., and Burt, D.M., 1986, The Geology and Geochemistry of Cenozoic Topaz Rhyolites from the Western United States: Geological Society of America Special Paper 205, 82 p.
- Hoffman, M.A., 1987, The Southern Complex: Geology, Geochemistry, Mineralogy and Mineral Chemistry of Selected Uranium- and Thorium-Rich Granites: unpublished PhD dissertation, Michigan Technological University, 382 pages.
- Jackson, N.J. and Ramsay, C.R., 1986, Post-Orogenic Felsic Plutonism, Mineralization and Chemical Specialization in the Arabian Shield: Transactions of the Institute of Mining and Metallurgy (Sect. B: Appl. earth sci.), v. 95, p. B83-B93.
- Kinnaird, J.A., Batchelor, R.A., Whitley, J.E., and MacKenzie, A.B., 1985, Geochemistry, Mineralization and Hydrothermal Alteration of the Nigerian High Heat Producing Granites, in High Heat Production Granites, Hydrothermal Circulation and Ore Genesis: Institute of Mining and Metallurgy, p. 169-195.
- Klasner, J.S., King, E.R., and Jones, W.J., 1985, Geologic Interpretation of Gravity and Magnetic Data for Northern Michigan and Wisconsin, in Hinze, W.J., editor, The Utility of Regional Gravity and Magnetic Anomaly Maps: Society of Exploration Geophysicists, p. 267-286.
- Streckeisen, A., 1976, To Each Plutonic Rock Its Proper Name: Earth Science Reviews, v. 12, p. 1-33.

The Mountain Shear Zone--Relevance to age of quartzite at McCaslin and
Thunder Mountains, northeastern Wisconsin

P.K. SIMS and Z.E. PETERMAN, U.S. Geological Survey, Denver, CO 80225;
J.S. KLASNER, Western Illinois University, Macomb, IL 61455

The Mountain shear zone is a discrete, 1- to 2.5-km-wide zone of mylonitic rocks that trends N.55°-60° E. and largely obliterates the regional north-trending fabrics (S_0/S_1) in metavolcanic and granitoid rocks of early Proterozoic (~1860 Ma) age (Sims and others, 1986; Sims, in press). An undeformed quartz diorite body (Hines Quartz Diorite) body that intruded the shear zone has a U-Pb upper intercept age of 1812.7±3.6 Ma, which provides a firm minimum age on the shearing.

A deformed conglomerate (Baldwin Conglomerate) within the shear zone contains clasts of granitic gneiss and metavolcanic rocks derived from the evolving shear as well as clasts of quartzite as much as 25 cm in diameter (Lahr, 1972). The source for quartzite clasts almost certainly was the quartzite now exposed at McCaslin and Thunder Mountains, less than 20 km to the north. Thus, inasmuch as the Baldwin Conglomerate was deformed during the shear deformation, and prior to emplacement of the Hines Quartz Diorite, the quartzite clasts and their parent rocks are older than 1812 Ma. The quartzite at McCaslin and Thunder Mountains unconformably overlies the Waupee Volcanics (Olson, 1984), which were deformed on northeast-trending fold axes and metamorphosed prior to quartzite deposition. The quartzite was deformed later into a westward-plunging syncline (Mancuso, 1960).

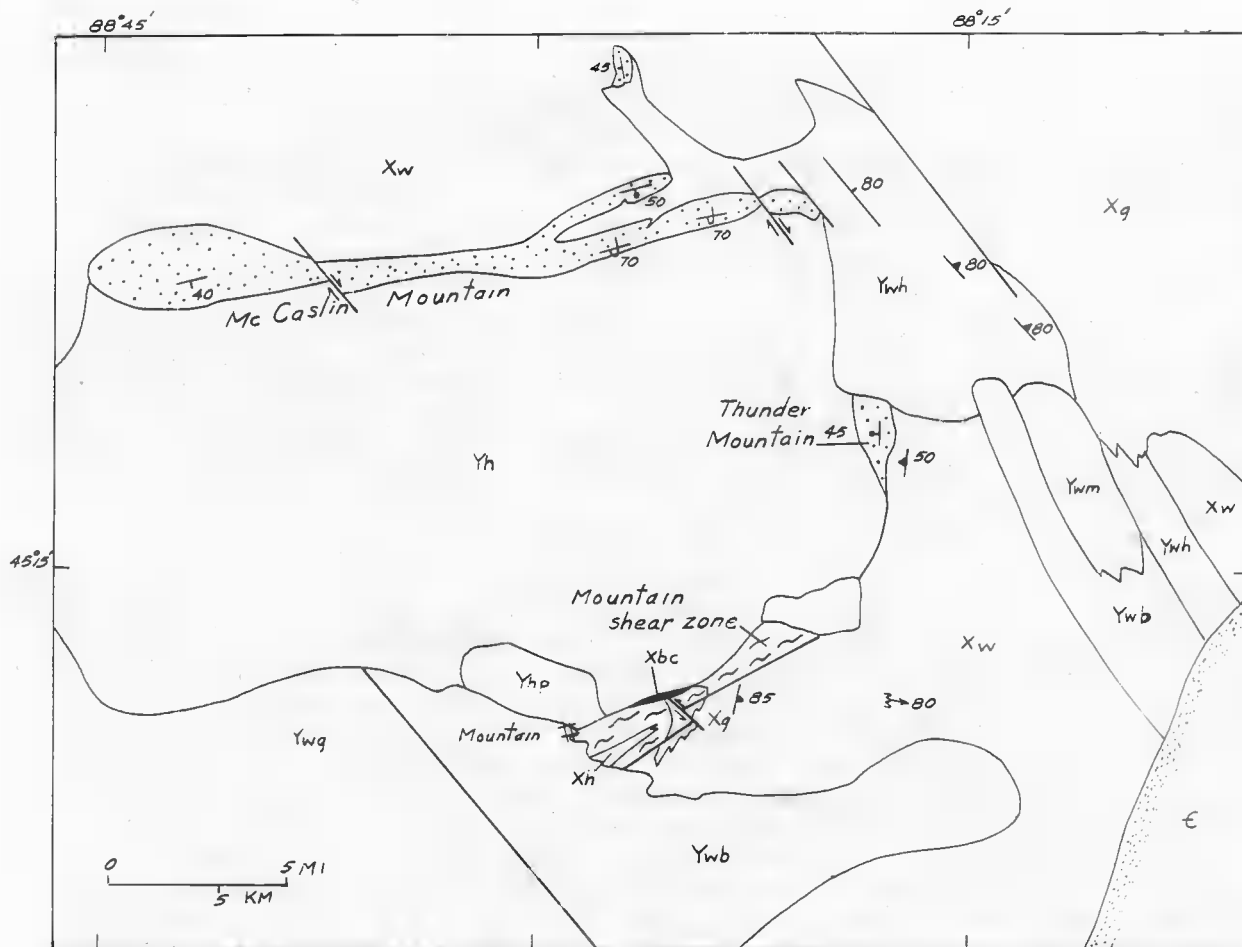
The quartzite bodies in the Lake Superior region show a great disparity in intensity of deformation, yet all of them generally have been presumed to be younger than 1760 Ma (see Van Schmus and Bickford, 1981), inasmuch as the Baraboo Quartzite in southern Wisconsin disconformably overlies 1760 Ma rhyolite (Dalziel and Dott, 1970; Van Schmus, 1978, 1980). The establishment of the quartzite at McCaslin and Thunder Mountains as being older than 1812 Ma suggests that other strongly deformed quartzite bodies, such as the Flambeau Quartzite, 160 km to the west, possibly are of comparable age. Perhaps these quartzites were deposited during a tectonically quiescent interval between ~1850 Ma and 1812 Ma.

Because the quartzite bodies in the north-central United States may differ in age by as much as 50 Ma, or perhaps more, and have undergone different tectonic histories, the term "Baraboo interval" (Dott, 1983) should be restricted to those quartzite bodies known to be younger than 1760 Ma.

REFERENCES CITED

- Dalziel, I.W.D., and Dott, R.H., Jr., 1980, Geology of the Baraboo District, Wisconsin: Wisconsin Geological and Natural History Survey Information Circular 17, 164 p.
- Dott, R.H., Jr., 1983, The Proterozoic red quartzite enigma in the north-central United States: Resolved by plate collision?, in Medaris, L.G., Jr., ed., Early Proterozoic geology of the Great Lakes region: Geological Society of America Memoir 160, p. 129-141.

- Lahr, M.M., 1972, Precambrian geology of a greenstone belt in Oconto County, Wisconsin and geochemistry of the Waupee metavolcanics: M.S. thesis, University of Wisconsin, Madison, 62 p.
- Mancuso, J.J., 1960, Stratigraphy and structure of the McCaslin District, Wisconsin: Ph.D. thesis, Michigan State University, East Lansing, 101 p.
- Olson, J.M., 1984, The geology of the lower Proterozoic McCaslin Formation, northeastern Wisconsin: *Geoscience Wisconsin*, v. 9, p. 1-19.
- Sims, P.K., in press, Geologic map of Proterozoic rocks near Mountain, Oconto County, Wisconsin: U.S. Geological Survey Miscellaneous Investigations Series Map I-1903, scale 1:24,000.
- Sims, P.K., Day, W.C., and Klasner, J.S., 1986, The Early Proterozoic Mountain shear zone, northeastern Wisconsin: *Geological Society of America Abstracts with Programs*, v. 18, p. 752.
- Van Schmus, W.R., 1978, Geochronology of the southern Wisconsin rhyolites and granites: *Geoscience Wisconsin*, v. 2, p. 19-24.
- Van Schmus, W.R., 1980, Chronology of igneous rocks associated with the Penokean orogeny in Wisconsin, in Morey, G.B., and Hanson, G.N., eds., *Selected studies of Archean gneisses and lower Proterozoic rocks, southern Canadian Shield*: Geological Society of America Special Paper 182, p. 159-168.
- Van Schmus, W.R., and Bickford, M.E., 1981, Proterozoic chronology and evolution of the Midcontinent region, North America, in Kroner, A., ed., *Precambrian plate tectonics*, Elsevier Scientific Publishing Co., Amsterdam, p. 261-296.



EXPLANATION

PALEOZOIC (570 Ma and younger)



Cambrian sandstone

MIDDLE PROTEROZOIC (900-1600 Ma)



High Falls Granite



Belongia Granite



Hager quartz porphyry



Hager Rhyolite



Wolf River Granite



Mangerite

EARLY PROTEROZOIC (1600-2500 Ma)



Hines Quartz Diorite



Baldwin Conglomerate



Quartzite



Granite



Waupea Volcanics



Mylonite in Mountain shear zone

Bedding

Foliation

Fault

Fold

Geologic map of part of northeastern Wisconsin (Compiled by P.K. Sims, 1988)

Evolution of the Early Proterozoic Wisconsin magmatic
terrane of the Penokean orogen

P.K. SIMS, U.S. Geological Survey, Denver, CO 80225; K.J. SCHULZ, U.S. Geological Survey, Reston, VA 22092; Z.E. PETERMAN, U.S. Geological Survey, Denver, CO 80225; W.R. VAN SCHMUS, Department of Geology, University of Kansas, Lawrence, KS 66045

The Penokean orogen (fig. 1) is a major Early Proterozoic tectonic belt along the southern margin of the Archean Superior craton. It consists of a northern continental-margin assemblage that overlies an Archean basement and a southern volcanic-plutonic (oceanic arc) assemblage, termed the Wisconsin magmatic terrane. The two terranes were juxtaposed at about 1860 Ma along the Niagara fault, a 10-km-wide paleosuture zone containing a dismembered ophiolite (Schulz, 1987).

The Wisconsin magmatic terrane consists of two known subterrane separated by a 7-km-wide zone of high strain (Eau Pleine shear zone) presumed to be a paleosuture. The northern, and major, subterrane, which is exposed along a strike length of 275 km and across a width of 150 km, is composed dominantly of greenschist-facies, and locally, lower amphibolite-facies volcanic rocks deposited in the interval 1860-1870 Ma. These rocks are mainly calc-alkaline felsic to mafic volcanic rocks similar to volcanic sequences in recent island arcs, but include tholeiitic basalt compositionally similar to back-arc basin basalts and island-arc tholeiites (Schulz, 1984). A more restricted, younger, greenschist-facies volcanic succession (1840-1850 Ma) overlies older tholeiitic basalt near Wausau, in the area southeast of the Athens shear zone. It consists of felsic calc-alkaline volcanic rocks, also of island-arc affinity, and associated subvolcanic(?) quartz diorite (LaBerge and Myers, 1984).

The southern subterrane, exposed south of the Eau Pleine shear zone, consists of a low-grade felsic to mafic volcanic succession, approximately 1860 Ma old, which unconformably overlies a possibly continuous Archean basement. Interlayered with the volcanic rocks are ferruginous chert, quartzite, conglomerate, and carbonaceous argillite. The Archean gneisses are exposed widely in the major river valleys in central Wisconsin.

A moderately widespread red alkali-feldspar granite, 1835 Ma old, intrudes the volcanic rocks in the southern subterrane and the Wausau area. It is cogenetic with two known small patches of rhyolite, welded tuff, and volcanogenic graywacke (LaBerge and Myers, 1984) which probably are caldera related.

Granitoid rocks, mainly ranging in age from about 1860 Ma to 1760 Ma, compose about one-quarter of the exposed part of the Wisconsin magmatic terrane. Calc-alkaline (volcanic-arc) intrusive bodies (1840 Ma and older) characterize much of the northern subterrane. They are presumed to be of mantle origin modified by a subduction component. Near the Niagara fault zone in northeastern Wisconsin, the dominant granitic intrusive rocks are collision-zone intrusions, as defined by Harris and others (1986). They include both syn-collisional and post-collision plutons, and apparently were generated during continent-arc collision (~1860 Ma) from melting of continental lithosphere. They can be distinguished from volcanic-arc plutons

through their higher Nb and Ta values. The 1835 Ma and the still younger 1760 Ma granitic bodies are post-tectonic and have characteristics of A-type granites. Presumably they were derived as partial melts of evolved crust.

Structurally, the 1860-1870 Ma volcanic rocks in the northern subterrane have a dominant east-trending, steep foliation that is axial planar to tight folds and a related mineral or intersection lineation; primary structures commonly are partly preserved. The main east-trending structural grain is inferred to have resulted from north-south collision. It was modified subsequently by gneiss domes adjacent to the Niagara fault zone, emplacement of granitoid bodies, major faults of diverse orientation, and discrete (~1815 Ma) shear (ductile deformation) zones that locally obliterate older structures. The 1840-1850 Ma volcanic rocks southeast of the Athens shear zone dip steeply and are folded on northeast-trending axes, whereas the 1835 Ma volcanic rocks are virtually undeformed. In contrast, the ~1860 Ma volcanic rocks and Archean basement rocks in the southern terrane have a nearly pervasive steep stretching lineation and accompanying mylonite that is superposed on older Archean and Early Proterozoic structures. These mylonitic structures pre-date the 1835 Ma magmatism, and possibly resulted from arc-continent collision along the Eau Pleine shear zone at about 1840 Ma.

In summary, the Wisconsin magmatic terrane is a composite arc system that records a major interval of calc-alkaline and tholeiitic volcanism at 1860-1870 Ma and a more restricted younger interval of calc-alkaline volcanism at 1840-1850 Ma. Granitoid intrusive rocks accompanied and followed the volcanism. Following final assembly of the terrane at ~1840 Ma along the Eau Pleine shear zone, intraplate magmatism in the south produced post-tectonic, possibly caldera-related rhyolite and cogenetic alkali feldspar granite. This relatively local magmatism was followed by more widespread magmatism at 1760 Ma, which was coeval with the anorogenic rhyolite-granite magmatism in southern Wisconsin (Smith, 1983; Anderson and others, 1980).

REFERENCES CITED

- Anderson, J.L., Cullers, R.L., and Van Schmus, W.R., 1980, Anorogenic metaluminous and peraluminous plutonism in the mid-Proterozoic of Wisconsin, U.S.A.: *Contributions to Mineralogy and Petrology*, v. 74, p. 311-328.
- Harris, N.B.W., Pearce, J.A., and Tindle, A.G., 1986, Geochemical characteristics of collision-zone magmatism, *in* Coward, M.P., and Ries, A.C., eds., *Collision tectonics: Geological Society Special Publication* no. 19, p. 67-81.
- LaBerge, G.L., and Myers, P.E., 1984, Two Early Proterozoic successions in central Wisconsin and their tectonic significance: *Geological Society of America Bulletin*, v. 95, p. 246-253.
- Schulz, K.J., 1984, Volcanic rocks of northeastern Wisconsin, *in* Sims, P.K., Schulz, K.J., and Peterman, Z.E., eds., *Guide to the geology of the Early Proterozoic rocks in northeastern Wisconsin: Field trip 1, 30th Annual Institute on Lake Superior Geology, Wausau, Wisconsin*, 93 p.
- _____, 1987, an Early Proterozoic ophiolite in the Penokean orogen: *Geological Association of Canada Programs with Abstracts*, v. 12, p. 87.
- Sims, P.K., 1987, Metallogeny of Archean and Proterozoic terranes in the Great Lakes region--A brief overview: *U.S. Geological Survey Bulletin* 1694-E, p. 56-74.

Smith, E.I., 1983, Geochemistry and evolution of the early Proterozoic post-Penokean rhyolites, granites, and related rocks of south-central Wisconsin, U.S.A., in Medaris, L.G., Jr., ed., Early Proterozoic geology of the Great Lakes region: Geological Society of America Memoir 160, p. 113-128.

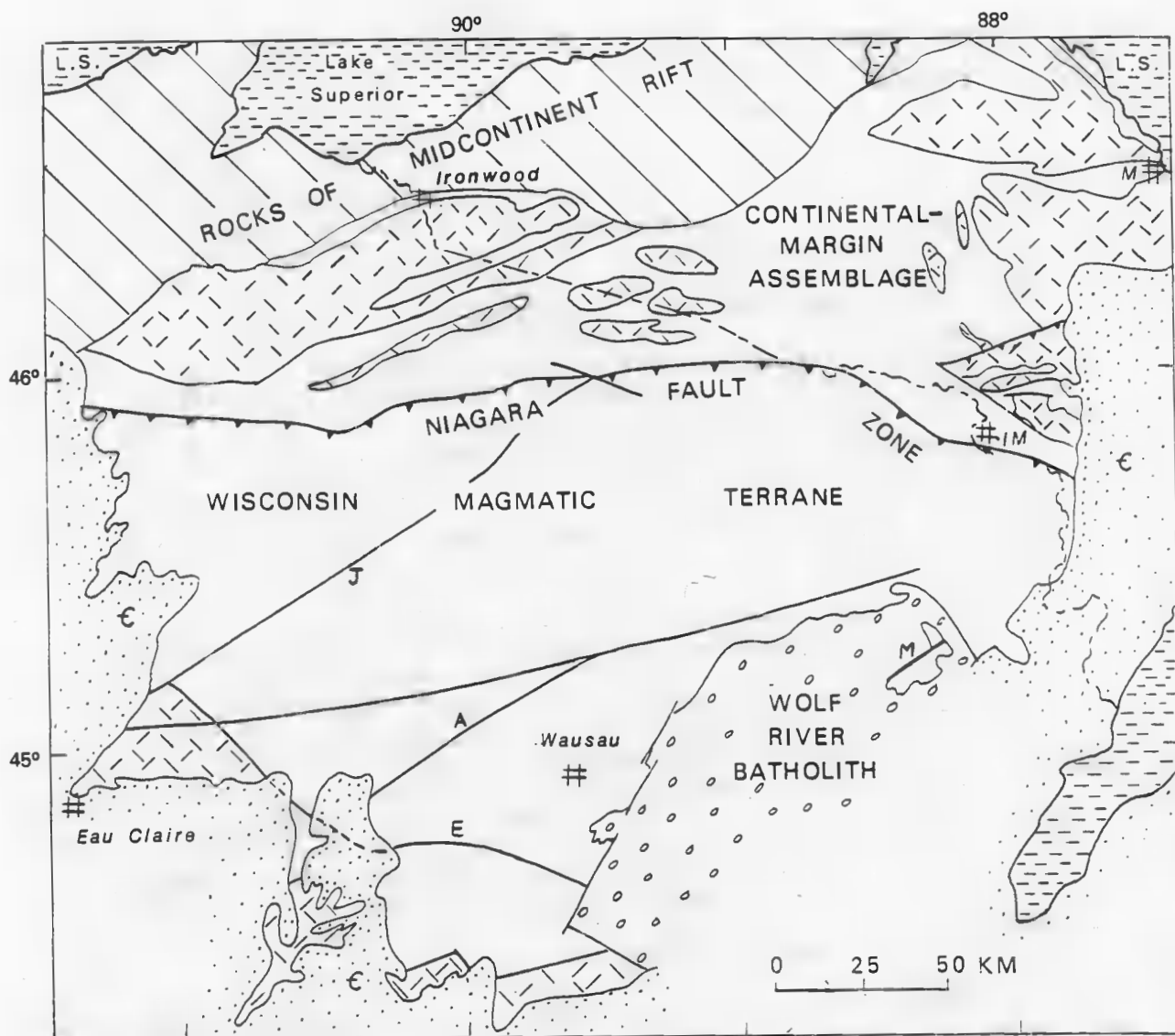


FIGURE 1. GEOLOGIC MAP OF PENOKEAN OROGEN, EASTERN LAKE SUPERIOR REGION, SHOWING CONTINENTAL-MARGIN ASSEMBLAGE AND WISCONSIN MAGMATIC TERRANE. (Modified from Sims, 1987.) Crosshatch pattern, Archean gneiss; blank areas, Early Proterozoic rocks; €, Paleozoic strata. E, Eau Pleine shear (suture) zone; J, Jump River shear zone; A, Athens shear zone; M, Mountain shear zone. IM, Iron Mountain; M, Marquette.

**The Reany Creek Formation, Northern Marquette County, Michigan:
Archean or Proterozoic?**

J.R. SMALL and T.J. BORNHORST (Department of Geology and Geological Engineering, Michigan Technological University Houghton, MI 49931)

The Reany Creek Formation consists of a variety of clastic sediments and crops out in an E-W trending elongate belt, less than 1.5 km wide, along the north shore of the Dead River Storage Basin in Marquette County. There are three stratigraphic units (Puffett, 1969): 1) a basal conglomerate composed of an eastern lens in sections 2 and 3, T48N, R26W, a western lens in section 6, T48N, R26W, and the Breccia of Holyoke Mine of Owens and Bornhorst (1985); 2) a middle succession of slate and greywacke with dispersed clasts (dominantly plutonic); and 3) an upper unit of arkose, quartzite, slaty greywacke, and conglomerate. The basal sediments unconformably overlie, or are in fault contact with Archean volcanic rocks to the north. To the south, the upper unit is in fault contact with Archean volcanic rocks. Clasts were sampled throughout the formation and include: granite, granodiorite, rhyolite, mafic volcanics, slate, and iron-formation.

Both the age of the formation and its mode of origin have been debated. It has been proposed as Archean to Lower Proterozoic in age and parts of it have been interpreted to be either tillite (Puffett, 1969) or a mass flow deposit (Mattson, 1983). This study focused on the question of the age of the formation. VanHise and Leith (1911) assigned the unit to the Upper Huronian due to the presence of iron-formation clasts which they thought to be Middle Huronian. However, these clasts are quite similar to the iron-formation found to the north in the Archean stratigraphic succession and similar to iron-formation within the Reany Creek Formation as described by Owens and Bornhorst (1985). W. A. Kelly (1936, in Engel, 1954) referred to the unit as being Timiskaming, or sub-Huronian (Archean), in age based on lithology and on an angular unconformity between slates and a quartzite correlated as Lower Proterozoic. Engel (1954) assigned the unit to the sub-Huronian, but stated there was a possibility that it was Middle or Lower Huronian. Puffett (1969) named the unit, Reany Creek Formation, and suggested a Lower Proterozoic age. However, he also stated that it could be equivalent to the Timiskaming. Owens and Bornhorst (1985) favored an Archean age for the Breccia of Holyoke Mine (basal conglomerate). At the Holyoke Mine Area, they observed that the basal conglomerate is deformed, and that folds in iron formation are vertically plunging, a style of deformation more like the Archean than the Lower Proterozoic. A shear zone follows the basal contact of the Reany Creek Formation (Breccia of Holyoke Mine) for about 2 km until it is entirely within Archean rocks (MacLellan and Bornhorst, this volume). Finally, Weeks (1987) concluded that the Reany Creek Formation filled a basin which was truncated as a result of Archean faulting along the Dead River Shear Zone.

Rhyolite dikes are common cutting Archean rocks. No such dikes cut sediments of Lower Proterozoic age in the Marquette area. Geologic mapping by Puffett (1969) showed no rhyolite dikes cutting the Reany Creek Formation. Two possible dikes were found in the basal unit. In one locality, there is a poorly exposed tabular rhyolite body, .5 meters by 10

meters, at an oblique angle to bedding. This exposure could be either a dike or an unusually large, elongate clast. In another locality, a well exposed tabular rhyolite body cuts a schist. Identification of the parent to the schist is uncertain. It may be Archean volcanics or sediments of Reany Creek Formation. If Archean, the rhyolite and surrounding schists are part of a fault bounded block. Unfortunately, these data are inconclusive with respect to the age of the Reany Creek Formation.

The age of the Reany Creek Formation is equivocal. The formation is in unconformable or fault contact with Archean rocks. There is no evidence to rule out conclusively an Archean or an Early Proterozoic age. It should not be presumed that the Reany Creek Formation is Early Proterozoic in age.

REFERENCES

- Engel, T. Jr. (1954) The Stratigraphy and Petrography of the Holyoke Meta-sediments of the Dead River Basin, Marquette County, Michigan, [M.S. Thesis]: East Lansing, Michigan State University, 72p.
- Mattson, S.R. (1983) The Reany Creek Formation: a Mass Flow Deposit of Possible Post Menominee Age: Proceedings and Abstracts, 29th Institute on Lake Superior Geology, Houghton, MI., 1983, p.27
- Owens, E.O. and Bornhorst, T.J. (1985) Geology and precious metal mineralization of the Fire Center and Holyoke Mines Area, Marquette County, Michigan: Michigan Geological Survey Division, Department of Natural Resources, Open File Report OFR-85-2, 105p.
- Puffett, W.P., (1969), The Reany Creek Formation, Marquette County Michigan, U.S. Geological Survey Bulletin 1274-F, 25 p.
- VanHise, C.R., and Leith, C.K., (1911) The Geology of the Lake Superior Region; U.S. Geological Survey Monograph 52, p. 287-288
- Weeks, V.L., (1987) Gravity and Magnetic Investigations in the South-Central Part of the Ishpeming Greenstone Belt, Marquette Co. Michigan, [M.S. Thesis]: Houghton, Michigan Technological University, 60 p.

TECTONIC IMBRICATION AND FOREDEEP DEVELOPMENT IN THE PENOKEAN OROGEN, EAST-CENTRAL MINNESOTA

D.L. Southwick and G.B. Morey

Minnesota Geological Survey, 2642 University Avenue, St. Paul, MN 55114

Geophysical data (chiefly aeromagnetic), together with the results of scientific and industrial drilling, have led to the recognition of several structural discontinuities within the Cuyuna iron-mining district and contiguous terrane in east-central Minnesota. These discontinuities separate structural panels of differing stratigraphy, structural style, and metamorphic grade, and appear to be zones of thrust faulting. Regionally the thrust-faulted, tectonically imbricated terrane constitutes a fold-and-thrust belt that was emplaced onto the southern margin of the Superior craton early in the deformational history of the Penokean orogen. Imbricate thrusting and recumbent folding may have begun as early as the time interval 2130-2180 m.y. and continued episodically for 300 m.y. or more. From south to north the thrust-bounded structural panels contain rocks metamorphosed at successively shallower crustal depth; deformation occurred under conditions ranging from amphibolite facies in the southernmost McGrath-Little Falls panel (Fig. 1) to lower greenschist facies in the North range of the Cuyuna district.

Geophysical and drilling data also indicate that the east-northeast structural trends of the fold-and-thrust belt are overlapped unconformably on the north by the lower strata of the Animikie Group along the south margin of the main bowl of the Animikie basin (Fig. 1). The deformation within the main bowl decreases regionally and systematically from south-southeast to north-northwest, until, along the Mesabi iron range at the north margin of the basin, the unfolded basal strata of the Animikie Group dip gently southward and rest with angular unconformity on Archean basement. We interpret the main bowl of the Animikie basin to be a tectonic foredeep that developed as a flexural response to loading of continental crust by thrust sheets and nappes in the fold-and-thrust belt to the south. Tectonic transport was from south-southeast to north-northwest, and the Animikie foredeep probably migrated cratonward in the same sense.

Finally, geophysical and drilling data have revealed two other basins filled by sedimentary strata comparable to the Animikie Group that lie between the fold-and-thrust terrane of the Cuyuna district and the cratonic foreland of Archean rocks. These, named the Long Prairie basin and the Nimrod outlier (Fig. 1), are interpreted to be remnants of the formerly more extensive Animikie foredeep.

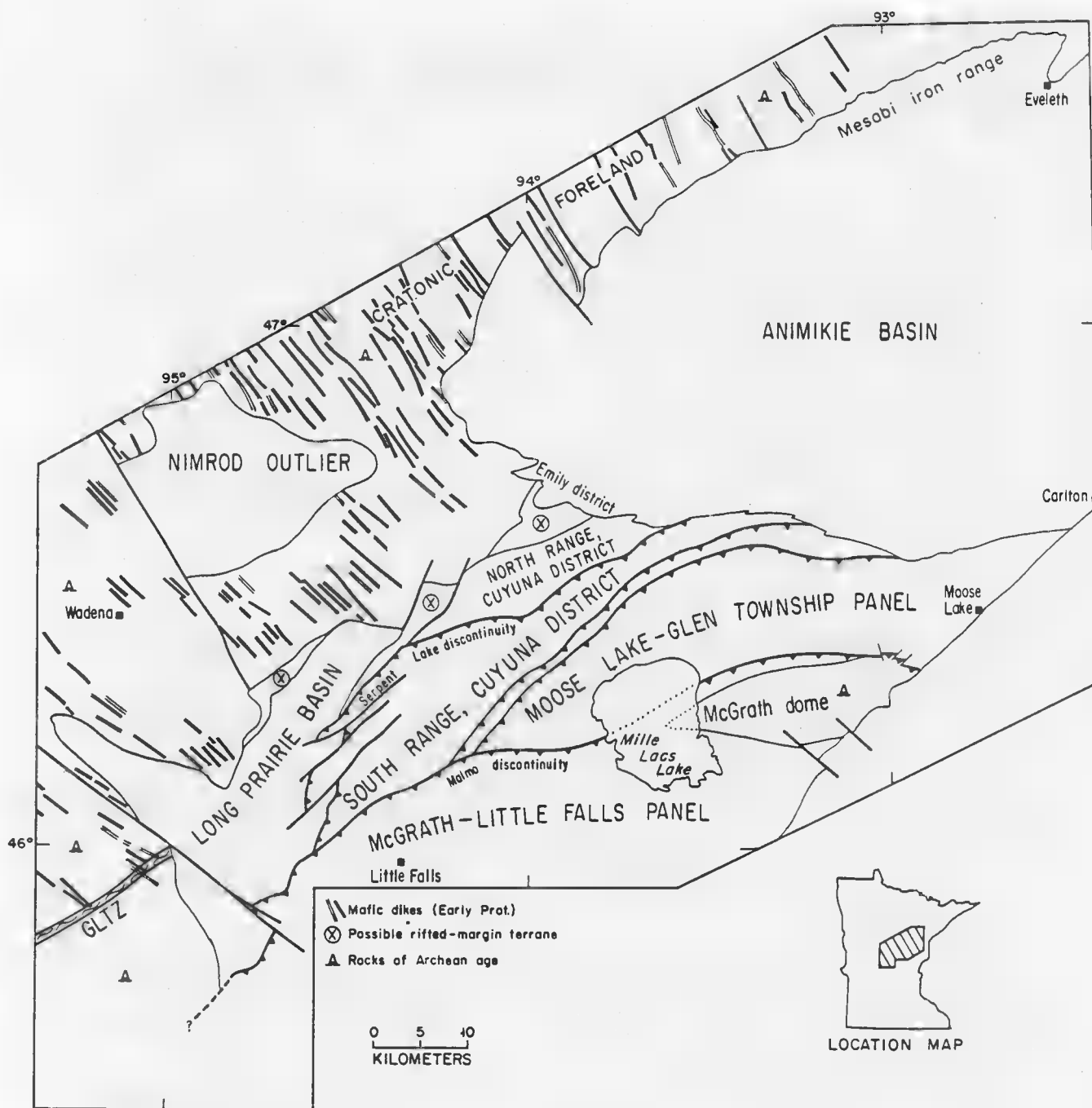


Figure 1. Generalized tectonic map of the Penokean orogen of east-central Minnesota. A fold-and-thrust belt of Early Proterozoic age consists of the McGrath-Little Falls, the Moose Lake - Glen Township, and the Cuyuna South range structural panels; the panels are bounded by structural discontinuities inferred to involve significant thrusting. The North range of the Cuyuna district is interpreted as an early foredeep that has been tectonically incorporated in the external zone of the fold-and-thrust mass. A major foredeep of Early Proterozoic age, but consequent to some and perhaps much deformation in the fold-and-thrust belt, consists of the Animikie basin, the Long Prairie basin, and the Nimrod outlier. The sedimentary fill of these basins rests unconformably on cratonic basement of Archean age along the northwest margins of the basins.

EARLY PENOKEAN DEFORMATION IN THE PEAVY POND AREA, NORTHERN MICHIGAN:
EVIDENCE FROM THE MICHIGAMME FORMATION AND THE PEAVY POND IGNEOUS COMPLEX
Steven D. Stahl and David J. Matty, Geology Dept., Central Michigan Univ., Mt. Pleasant, MI
48859

INTRODUCTION

In the Peavy Pond area of northern Michigan, the Early Proterozoic Michigamme Formation was intruded by the Peavy Pond igneous complex (PPC). Both units were deformed and metamorphosed during the Proterozoic Penokean orogeny (e.g., Attah, 1984, 1986 a, b). Detailed structural analysis of the macroscopic fabric elements in the Michigamme Formation in and adjacent to the PPC supports an arc-continent collision model with north over south shortening. The dominant Penokean structure is a north-closing fold nappe with the PPC in the core and the upper and lower limbs juxtaposed by postnappe faulting associated with the Bush Lake Fault (BLF).

OBSERVATIONS OF STRUCTURAL FEATURES

For ease of presentation, we have subdivided the study area into the following domains: Domain 1 consists of the Michigamme Formation north of the BLF and adjacent to the PPC; Domain 2 comprises enclaves of Michigamme Formation within the PPC; Domain 3 includes igneous rocks of the PPC; and Domain 4 contains rocks of the Michigamme Formation to the south of the BLF and adjacent to the PPC.

Domain 1

Minor folds dominate the structural fabric of the greenschist to amphibolite facies Michigamme Formation exposed to the north of the BLF. Six generations of folds are recognized. The oldest three generations (F1, F2, F3) predate regional metamorphism. They possess the following common characteristics: 1) absence of axial planar foliation; 2) consistence with WSW-ENE shortening; 3) asymmetry indicative of WSW to ENE overridding; 4) quartzo-feldspathic layers defining Class 1 folds; 5) micaceous layers defining Class 3 folds; and 6) rounded hinges and the reduction of hinge to limb ratio with decreasing age. F1, F2, and F3 appear to be coaxial, but the data are not conclusive in part due to their insufficient number but also due to their reorientation by subsequent polyphase deformation. F1 are tight to isoclinal folds of beds (S0). F2 are close to tight, shallowly to moderately inclined (with respect to F1 axial surfaces (S1)) folds of S0 and S1. F3 are open to close, moderately to steeply inclined (with respect to S1) folds of S0, S1, and F2 axial surfaces (S2).

Younger folds are markedly different from F1-F3 in style, attitude, and geometry: apparently synmetamorphic F4 folds are almost ideal chevrons (interlimb angle close to 70°, hinge region very small) of early S-surfaces with moderately well developed axial planar foliation (S4) in the hinge. The sense of S4 asymmetry indicates N-S shortening and northward overridding which is consistent with Penokean kinematics (e.g. Cambray, 1978).

Fifth and sixth generation folds are open to gentle. F5 is defined by a N80W-N80E striking, steeply dipping foliation (S5); it is consistent with N-S shortening and is post-F4 because S5 is neither parallel to S4 nor folded by F4. F6 folds S5; this generation is consistent with E-W shortening. F5 and F6 are regional deformations present in several Penokean terranes.

Domain 2

Enclaves of the Michigamme Formation within the PPC are characterized by minor folds with superimposed equigranular texture that is locally foliated. These folds are correlated to Domain 1 F1, F2, and F3 because they are similar in style. F1-F3 therefore predate the intrusion of the PPC. Because Domain 2 Michigamme rocks are stoped blocks, attitude measurements of fabric elements in these blocks are moot; parallelism of Domain 2 surfaces with Domain 1 surfaces may or may not be fortuitous. Nonetheless, the orientation of the foliation superimposed on the xenolithic blocks is steeply dipping and strikes N80E-N80W. The equigranular texture was

developed by contact metamorphism, and the event which produced the late-stage foliation postdates PPC emplacement.

Domain 3

Two steeply dipping foliations are present in the PPC on both sides of the BLF; one strikes N80E-N80W and is crosscut by the second, which strikes N10-20E. On the basis of parallelism of surfaces, the former is correlated to Domain 1 F5 and the latter is correlated to Domain 1 F6.

Domain 4

Domain 4 consists of sillimanite-grade Michigamme Formation exposures to the south of the BLF and adjacent to the PPC. Minor folds are ubiquitous, but they have been flattened to tight to isoclinal with quartzo-feldspathic layers defining Class 2 folds. This flattening makes differentiation and correlation of Domain 4 folds to Domain 1 F1, F2, or F3 impossible.

Ductile boudinage and flattened garnets are prevalent in these exposures. Estimates, that are necessarily low and assume no volume strain, of finite extension derived from the measurement of boudins range from 75 to 85 percent; in flattened garnets the estimated finite extension ranges from 95 to 105 percent. The mean finite strain ellipsoid is oriented such that: 1) the intermediate axis plunges shallowly and trends approximately E-W; 2) the maximum extension axis plunges shallowly and trends N-S; and 3) the maximum compression axis is near vertical.

The presence of rolled garnets, rolled boudins, and folded boudins indicate that the mechanism of deformation was not pure shear but instead extreme simple shear with near horizontal shear plane and N-S trending shear direction. This event is correlative to Domain 1 F4 because it is syn-metamorphic; moreover, the closure direction and sense of asymmetry (S over N) are the same in both domains.

INTERPRETATIONS

The PPC and surrounding Michigamme Formation define a Penokean fold nappe (recumbent fold, allochthonous, extreme simple shear in lower "short" or "overturned" limb and parasitic folds in upper "upright" limb). Nappes with faulted lower limbs have been documented elsewhere in the Penokean fold belt (e.g. Holst, 1984), but the recognition of a ductile lower limb is apparently unique to the Peavy area. The PPC is in the core of the nappe and the BLF juxtaposes the upper (Domain 1) and lower (Domain 4) limbs. The extreme simple shear associated with the development of the Penokean fold nappe obscured the early fabric elements in the lower limb - this reorientation prohibits the recognition of early Penokean events in rocks of this limb, which comprise the overwhelming majority of exposures in the Peavy Pond area.

Structural analysis of the Michigamme Formation in and adjacent to the PPC indicates that the structures associated with the Penokean orogeny are compatible only with an arc-continent collision model similar to that proposed by Cambray (1978). Our work also implies, however, that the paleogeography must have been more complex than has been proposed previously.

REFERENCES

- Attoh, K., 1984, Some constraints on the thermal causes of Early Proterozoic metamorphic zones in northern Michigan: Geol. Assoc. Can. - Min. Assoc. Can. Ann. Meeting.
- Attoh, K., 1986a, Metamorphic pressures, temperatures and Early Proterozoic geotherms in northern Michigan: 32nd Annual Meeting Institute on Lake Superior Geology.
- Attoh, K., 1986b, Early Proterozoic crustal geotherms during Penokean metamorphism in northern Michigan: Geol. Assoc. Can. - Min. Assoc. Can. Ann. Meeting.
- Cambray, F., 1978, Plate tectonics as a model for the environment of deposition and deformation of the Early Proterozoic (Precambrian X) of northern Michigan: Geol. Soc. Am. Abst. w. Prog., 10, p. 376.
- Holst, T. B., 1984, Evidence for nappe development in the Early Proterozoic Penokean orogeny, Minnesota: Geology, 12, p. 135-138.

DEFORMATION HISTORY OF THE QUETICO METASEDIMENTS ALONG THE NORTHERN MARGIN OF THE VERMILION GRANITIC COMPLEX, NORTHERN MINNESOTA.

Tabor, J.R., and Hudleston, P.J., Dept. of Geology and Geophysics, University of Minnesota, Minneapolis, MN, 55455.

Amphibolite-grade (M_1) pelitic schists and younger minor leucogranites and pegmatites of the Rainy Lake District in northern Minnesota dominate the E-W trending belt of Archean supracrustals that borders the northern margin of the higher-grade migmatites and gneisses of the Vermilion Granitic Complex (VGC), the southwestern extension in northern Minnesota of the Quetico Gneiss Belt. The structural development of the schist belt involved the temporal partitioning of the strain associated with a dynamic dextral transpressive deformation involving both E-W dextral shear and N-S horizontal flattening.

The early stage of deformation involved two phases of pervasive folding, the first possibly recumbent and nappe-like and the second upright and isoclinal. Minor folds across much of the width of the schist belt are preodominantly F_2 and of 'Z' symmetry, with minor 'perturbed' areas of 'S' symmetry representing either undulations in the hinge lines of minor F_2 folds or major F_2 folds. However, approaching the southern margin of the schist belt minor F_2 folds of 'S' symmetry are dominant in the schists (Bauer, 1988), suggesting that a major F_2 fold does indeed underlie the schist belt whose northern limb forms much of the width of the belt. Reversal in stratigraphic tops from north- to south-facing across the northern limb of this major F_2 fold suggests the presence of a major F_1 fold. Minor F_1F_2 fold interference patterns also support this.

Meso- and microstructural evidence along the Rainy Lake-Seine River Fault (RLSRF), the major fault defining the boundary between the schist belt and the Rainy Lake Wrench Zone to the north, suggest E-W near-horizontal dextral shear dominated the intermediate stage of the transpressive deformation and was localized into the RLSRF as the schists along the northern margin of the belt cooled from amphibolite- to greenschist-facies conditions.

The lack of evidence for shear, the presence of tectonized pegmatite veins crosscutting F_1F_2 fold interference patterns and the presence and orientation of conjugate shear bands and zones in the

leucogranites and pegmatites suggest the N-S horizontal flattening component of the transpression dominated the later stages of the deformation. Quartz and calcite lattice preferred orientation (LPO) analyses also suggest an increased dominance of a ductile component of N-S horizontal flattening in the **RLSRF** during greenschist-facies conditions. In the center of the schist belt, quartz LPO patterns suggest: 1) the schists bordering the leucogranites and pegmatites have also experienced both E-W dextral shear and N-S flattening, 2) schists located away from the intrusives have experienced only E-W dextral shear and 3) the leucogranites and pegmatites have experienced only N-S horizontal flattening. Quartz LPO patterns from the southern margin of the schist belt bordering the migmatite terrane to the south were similar to those measured along the northern margin of the belt in the **RLSRF** and to those in the schists enveloping the margins of the leucogranites and pegmatites in the center of the belt, indicating the schists to the south have also experienced both E-W dextral shear and N-S flattening.

It is suggested that this sequence of structural development and partitioning of strain across the width of the schist belt is a consequence of the rotation of the regional kinematic framework of deformation and temporal variations in the ductility of the schists and intrusives. Initially, while bedding was near-horizontal, the schists accommodated the coaxial component of the transpression and deformed homogeneously by pervasive folding. Minor noncoaxial strain from this episode of the deformation is recorded in the asymmetric quartz LPO patterns in schists in the center of the belt. Following pervasive upright and isoclinal F_2 folding, the schists were in a favorable orientation to accommodate the noncoaxial component of the transpression. However, the schists were also cooling, and therefore hardening, such that E-W dextral shear was heterogeneously localized into the **RLSRF** along the northern margin of the belt. Subsequently, the regional kinematic framework rotated such that ductile N-S horizontal flattening occurred in the: 1) **RLSRF**, 2) leucogranites and pegmatites and schists enveloping their margins and 3) schists along the southern margin of the belt bordering the migmatite terrane to the south. The bulk of the schist belt deformed by brittle faulting during this stage of the deformation.

The increased ductility necessary for the aforementioned areas to accommodate the late component of N-S horizontal flattening was a consequence of: 1) strain heating in the **RLSRF** along the northern

margin of the schist belt, 2) contact heating supplied by the plutons in the center of the belt and 3) regional metamorphic heating supplied by the VGC along the southern margin of the belt. At this time, the reasons and tectonic significance of the rotation of the regional kinematic framework are unclear.

Bauer, R.L., 1988, Multiphase folding....., this volume.

REFRACTION ANALYSIS OF THE GLIMPCE MARINE REFLECTION PROFILE IN GEORGIAN BAY

Michael D. Thompson and C. Patrick Ervin

Dept. of Geology, N. Illinois Univ., DeKalb, IL 60115

In 1986, a multichannel, marine reflection survey was made along a profile across Georgian Bay and Lake Huron (GLIMPCE Line J) employing a streamer length of approximately 3 km. Part of the data within Georgian Bay, beginning with shotpoint 1598 north of Cabot Head and extending westward to shotpoint 2174 north of Cove Island in the entrance of the bay, were reprocessed using an automatic picking algorithm to obtain arrival times for the refracted energy. Both a refractor offset correction and a lake bottom topography correction were incorporated into the inversion of the first arrival data to obtain a velocity-depth section along the profile.

Preliminary analysis of the data shows the eastern portion to be dominated by laterally continuous, westward dipping ($<0.5^\circ$) refractors, probably of Ordovician age. The gentle dip is consistent with the regional geologic structure, and the computed velocities are within the range of values expected on the basis of the known lithologies in the area. Assuming that velocities on the order of 6.1 to 6.6 km/s mark the top of the Precambrian basement (Mereu and Jobidon, 1971), the interpreted velocity structure beneath this portion of the profile suggests that the depth of the westward deepening basement surface ranges from 300 to 400 m.

The western part of the profile track overlies near-surface, high-velocity Silurian dolomite, which tends to mask the refractions from underlying layers. In this instance, refractions from the Precambrian surface are not observed because they do not become the first arriving energy until beyond the limits of the receiving array. A further problem arises in the shallow water areas where bottom sediment refractions are often absent due to the large source-to-first-receiver distance relative to the refractor depth. Because refractor depths are calculated in a cumulative fashion, lack of information for the undetected shallow layers precludes calculation of reliable depths for the deeper interfaces.

This analysis demonstrates that marine reflection data can be reprocessed relatively cheaply to obtain additional information on the shallow velocity structure. However, the technique is ineffective in the extremely shallow water overlying the unusually-high, near-surface velocities found in the entrance to the bay.

REFERENCES CITED

- Mereu, R.F., and Jobidon, G., 1971, A Seismic Investigation of the Crust and Moho on a Line Perpendicular to the Grenville Front, Canadian Jr. of Earth Sci., v. 8, p. 1553-1583.

GEOCHEMISTRY AND PETROLOGY OF THE ATHELSTANE GRANITE.
MARINETTE COUNTY, WISCONSIN

R. J. Wagner and M. K. Sood
Department of Earth Sciences
Northeastern Illinois University
Chicago, Illinois, 60625

The Athelstane Granite lies in the northern part of Marinette County, northeastern Wisconsin. It is a roughly oval shaped pluton that covers an area of 226 mi.² (585 km.²). Van Schmus et al., (1975) obtained an Rb/Sr isotope age of 1810 $\pm$ 50 m.y. for the Athelstane Granite, and considered it to be a part of the Penokean Northeastern Wisconsin orogenic and plutonic complex. The Athelstane Granite has relatively sharp contact relations with the Quinnesec metavolcanics (1905 $\pm$ 50 m.y.). Quinnesec xenoliths in Athelstane are thermally altered. Locally, the Athelstane Granite is intruded by 1760 $\pm$ 10 m.y. old Amberg Granite (Van Schmus, 1980).

The Athelstane Granite is a medium to coarse grained pink granite with average modal composition of microperthitic microcline (39.1%), An₂₀₋₃₀ plagioclase (24.9%), bluish quartz (26.5%), biotite (3.8%), and hornblende (1.2%). Accessory minerals include apatite, sphene, and magnetite. Modal compositions plot in the Granite field of Streckeisen's (1976) quartz-alkali feldspar-plagioclase feldspar diagram. Micrographic growths are present.

Retrogressive reactions seen include sericitization of plagioclase, and the replacement of hornblende by biotite or chlorite.

Major element chemistry of the Athelstane rocks shows that they are calc-alkaline and marginally peraluminous. The SiO₂ varies between 67 to 75 weight %. K₂O, FeO, TiO₂, and P₂O₅ are high, whereas MgO, CaO and to a certain extent Na₂O, are low, when compared to granitoids with similar silica contents. K₂O is generally greater than Na₂O, with total alkalis (Na₂O+K₂O) between 6.1 to 8.5 weight %. The (K₂O+Na₂O)/CaO and FeO/(FeO+MgO) ratios of 1.5 to 3.5 and 0.75 to 0.86 respectively, are similar to anorogenic granite, but different from other Penokean granites. Harker variation diagrams (SiO₂ vs. other major oxides) show a limited role played by fractional crystallization. Both Zr (130-410 ppm.) and Ba (630-2380 ppm.) are relatively higher than other Penokean granites. Ba-Rb-Sr relations do not show extensive effects of metasomatism or late fluxing of magma with volatiles (El-Bouseily and El-Sokkary, 1975).

Petrographic, chemical (Figures 1-3), and field relations of the Athelstane Granite have greater affinity to anorogenic than synorogenic granite plutons. Clearly, the Athelstane Granite is a late orogenic (or perhaps even post orogenic) intrusion that certainly did not originate during the main stage of the Penokean orogeny.

Plots of the compositions of Athelstane rocks in the albite-orthoclase-silica system containing polybaric minima projections (Anderson, 1983), suggest that the granite magma was probably generated at approximately 35 km. depth, and emplaced at about 10 km. depth.

It is therefore proposed that the Athelstane Granite magma was generated by a moderate degree of partial melting of crustal material, probably a mixture of Archean and Penokean crust transitional to tonalite-gabbro composition.

This study was supported by a grant to M. K. Sood from the Committee on Organized Research.

Anderson, J. L., 1983, Proterozoic anorogenic granite plutonism of North America: *Geol. Soc. America Mem.* 161, p. 133-154.

Anderson, J. L., and Cullers, R. L., 1987, Crust-enriched, mantle-derived tonalites in the early Proterozoic Penokean orogen of Wisconsin: *Journal of Geology*, v. 95, p. 139-154.

El-Bouseily, A. M., and El-Sokkary, A. A., 1975, The Relation Between Rb, Ba, and Sr in Granitic Rocks: *Chemical Geology*, v. 16, p. 207-219.

Streckeisen, A. L., 1976, To each plutonic rock it's proper name: *E. Sci. Review*, number 12, P. 1-34.

Van Schmus, W. R., 1980, Geochronology of igneous rocks associated with the Penokean Orogeny in Wisconsin: in Morey, G. B., and Hanson, G. N., eds., *Selected studies of Archean and lower Proterozoic rocks, southern Canadian Shield*: *Geol. Soc. America Spec. Paper* 182, p. 159-169.

Van Schmus, W. R., Thurman, E. M., and Peterman, Z.E., 1975, Geology and Rb-Sr chronology of middle Precambrian rocks in eastern and central Wisconsin: *Geol. Soc. America Bull.*, v. 86, p. 1255-1265.

Figure 1

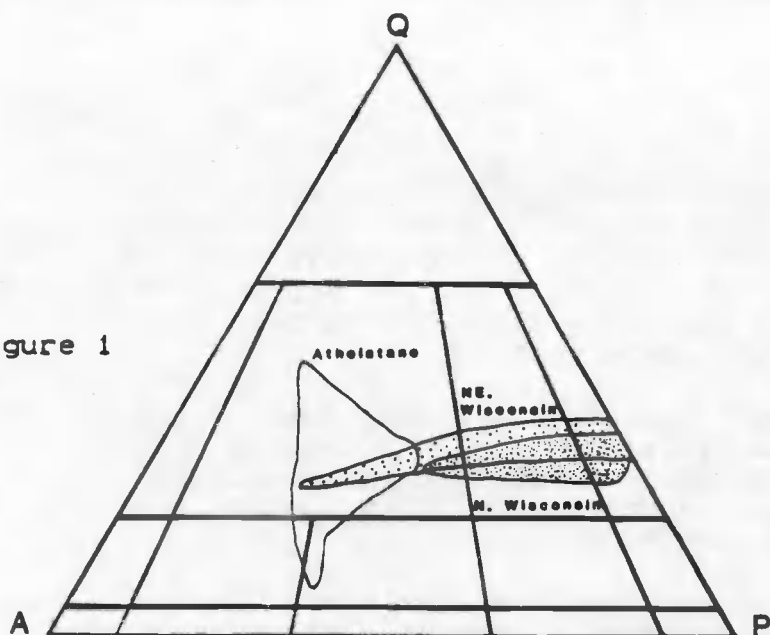


Figure 2

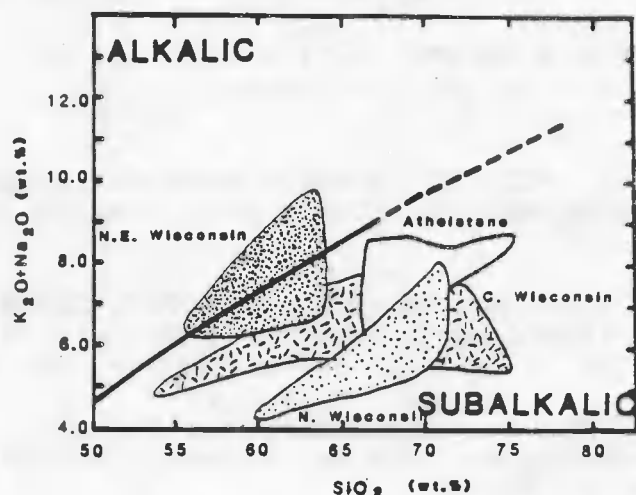
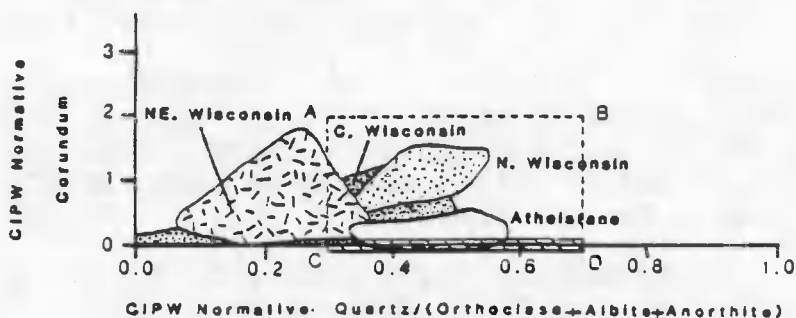


Figure 3



Figures 1-3. Figure 1 is a Q-A-P Diagram (modal Quartz-Alkali Feldspar-Plagioclase Feldspar) comparing the Athelstane pluton to the other Penokean plutons of northern and northeastern Wisconsin. Figure 2 is a plot of Total Alkalis ($K_2O + Na_2O$) vs. SiO_2 (weight %) for the Athelstane pluton compared to other Penokean plutons of Wisconsin. Figure 3 shows the CIPW-normative corundum vs. quartz/feldspar ratio for the Athelstane pluton compared to the other Penokean plutons of Wisconsin. Box ABCD is the zone of normal granites (from Fernandez-Alonso et al., 1986).

Geochemistry and Tectonic Significance of Early Proterozoic Igneous Rocks,
Northern Michigan and Northeastern Wisconsin

Soo Meen Wee and John T. Wilband, Department of Geological Sciences, Michigan State University, East Lansing, MI 48824

Early Proterozoic igneous rocks in northern Michigan and northeastern Wisconsin consist of a complex assemblage of lavas, sills and dikes. These rocks were metamorphosed at varying degrees during the Penokean Orogeny (1.82-1.85 Ga). The tectonic evolution of the area has been attributed to plate margin processes, arc-continental collision processes, or intracratonic mobilization.

The analyzed rocks fall within the tholeiitic field in an AFM diagram. A northern tholeiitic assemblage of dike swarms and volcanic piles containing pillow lavas (Hemlock and Badwater Greenstones) can be distinguished from a southern magmatic assemblage with arc-related chemical characteristics. Mafic rocks of the dike swarms, the Hemlock volcanics, and the Badwater Greenstones evolved from tholeiitic basalts with subalkaline affinities. Virtually all rocks plot within the subalkaline field of the Ol-Ne-Q diagram. The absence of the alkaline basalt field within the region could mean that early Proterozoic magmas were generated at relatively shallow depth, under the influence of a high geothermal gradient.

Based on chemical characteristics and CaO/TiO_2 and Al_2O_3 vs. TiO_2 plot, it can be suggested that the rocks of the northern assemblage are derivatives of hi-Ti MORB like tholeiites from relatively undepleted source(s). The elemental distributions of the lavas and dike swarms in the northern assemblage have led us to conclude that the dikes served as feeders to the volcanic piles.

Other data support contamination processes. For example, in some dikes, SiO_2 and Rb/Sr are enriched at the margins compared to the centers and may represent assimilation during emplacement or crystallization. The Zr/Y ratio for the supracrustal rocks (>10) is much higher than the more primitive flows and dikes. Evolved rocks with progressively higher Zr/Y ratios may have resulted from assimilation within ponded magma systems. Furthermore, Ce/Yb vs. Ce plots can be interpreted to represent assimilation-fractional crystallization rather than simple fractional crystallization. Finally, in spider plots of suite averages, the dike swarms, Hemlock volcanics, and Badwater Greenstones are distinctively depleted in Nb with respect to its neighboring elements, where the Nb anomaly is calculated as $\text{Nb}/\text{chon.} - (\text{Th}/\text{chon.} + \text{La}/\text{chon.})/2$ (Ueng et al., 1987). The decrease approximates an exponential function with increasing differentiation index. This implies continuing assimilation throughout the differentiation history.

The tectonic settings of the dike swarms, Hemlock volcanics, and Badwater Greenstones were tested by previously developed tectonic discrimination diagrams. In Ti-Zr-Y plots (Pearce), the majority of the rocks plot in the within plate basalt field, and a fairly large number in the calc-alkaline and ocean floor basalt region. In Nb-Zr-Y plot (Meschede), the data mostly fall in the within plate tholeiites and P-type MORBs. The subparallel "vertical" trends away from the Nb apex may reflect the aforementioned assimilation of crustal rocks depleted in Nb. The other possibility is that the P-type MORBs can be generated by gradual decompression during rifting. This decompression enabled concurrent melting of zoned source of upper, more depleted mantle and lower enriched mantle. In tectonic discrimination diagram using Hf-Ta-Th (Wood), most samples from this investigation plot outside the tectonic fields. This suggests that the rocks have been contaminated since Hf, Ta, and Th are very sensitive to crustal contamination. In summary, there is no clear definition of tectonic setting for the early Proterozoic rocks of the area. However, CaO/TiO_2 and $\text{Al}_2\text{O}_3/\text{TiO}_2$ vs. TiO_2 plots (Sun & Nesbitt), most of the northern assemblage rocks cluster along an undepleted source trend; whereas the southern

"magmatic arc" rocks of the Quinnesec plot in a depleted source region. Because arc-related rocks are commonly depleted in TiO_2 and are enriched in $\text{Al}_2\text{O}_3/\text{TiO}_2$ compared to MORBs or continental tholeiitic basalts, the rocks of the northern assemblage are probably best assigned as having a rift related origin. Interpretations of the chemical characteristics of these rocks, based on modern analogs, favor an extensional tectonic regime, such as would develop by arc-continent collision processes suggested by previous investigators.

Preliminary Structural Analysis of Archean Rocks in the Virginia
Horn area, Northeastern Minnesota

J.L. WELSH (Department of Geology, Gustavus Adolphus College,
St. Peter, MN 56082)

Detailed mapping in lower greenschist grade Archean rocks within the Virginia Horn area of northeastern Minnesota (the prominent Z-fold defined by the unconformable superjacent Biwabik Iron Formation of the Mesabi Iron Range), has revealed the presence of at least one major period of folding (F1) and a series of northeasterly trending faults which postdate the folding. The fold event is identified primarily on the basis of reversals in stratigraphic top indicators. Minor F1 folds are rare, but where present they are tight to isoclinal in style and steeply plunging. A moderately to well developed axial plane foliation is present in these folded rocks.

One prominent fault, here informally designated the Fayal fault, separates the greenstone occupying the ridge west of Gilbert with the greywacke-slate sequence present east of Eveleth (Fig.). Another fault, here informally designated as the Pike River fault, separates this same metasedimentary sequence from greenstone to the west, in the northern portions of the study area. Strongly phyllonitic rocks mark its presence. The Pike River fault is more difficult to delineate to the south as it appears to cut into the metasedimentary sequence and trends parallel to bedding. In this southern area the Pike River fault is interpreted to occupy a phyllonitic zone which separates a distinctive conglomeratic unit from the more turbiditic greywacke-slate sequence. Located between these two major faults occur a group of inferred subsidiary faults, that strike obliquely to the main fault trend. These subsidiary faults are identified by topographic lineaments, changes in strike of bedding (in the easternmost of these faults) and local silicification and/or sericite-carbonate alteration of the rocks along them.

The localization of alteration zones along some of these faults, and the occurrence of abundant sericite and carbonate in many of the metasedimentary rocks suggests that large volumes of fluids passed through these rocks, probably using the faults as conduits. Therefore these faults and their associated alteration zones may be useful guides for mineral exploration in the area.

The Pike River fault lies essentially on trend with the Waasa fault further to the northeast, and thus could have regional significance. The occurrence of these faults in the Archean rocks of the area also suggests a possible genetic relationship to the Proterozoic structure of the of the Virginia Horn itself.

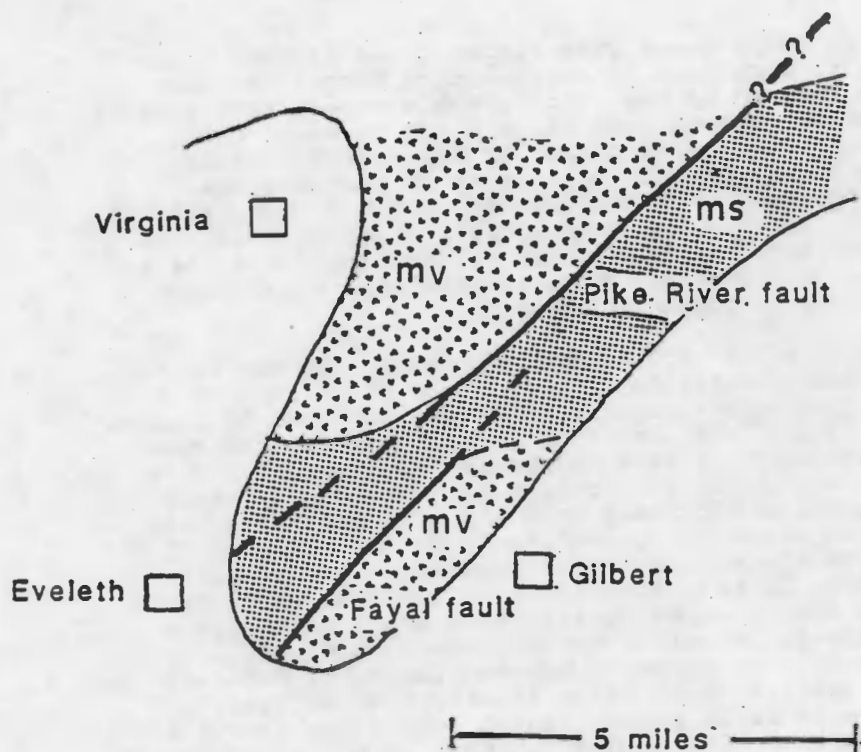


Fig. Sketch map of Archean rocks in the Virginia Horn area, showing the distribution of metasedimentary (ms) and metavolcanic (mv) rocks, and major faults. The boundary shown in the vicinity of the cities of Virginia, Eveleth, and Gilbert marks the unconformity between the Archean rocks and the superjacent Proterozoic rocks.