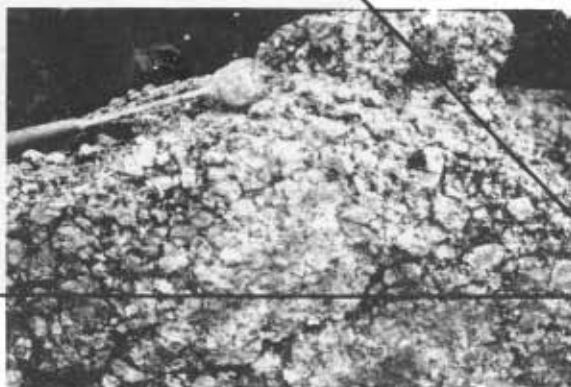
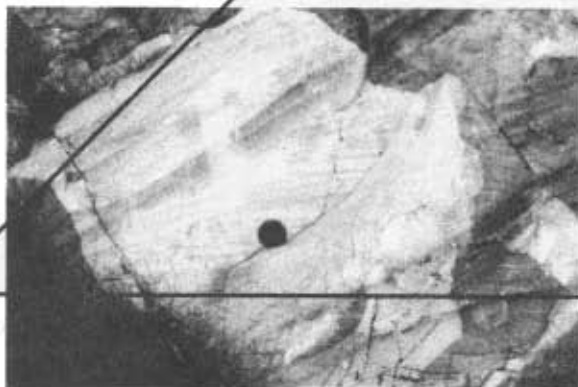




Thirty-Second Annual
Institute on Lake Superior Geology

Wisconsin Rapids, Wisconsin
April 29-May 4, 1986

ABSTRACTS



Sponsored by:

Wisconsin Geological and Natural History Survey
University of Wisconsin-Extension
Madison, Wisconsin

Cover photos: Top; banded gneiss in Stevens Point area,
Lower, right; adamellite porphyry in Wolf River batholith,
Lower left; cross-bedded orthoquartzite in Baraboo
interval sediments.

PROCEEDINGS AND ABSTRACTS

32ND ANNUAL INSTITUTE ON
LAKE SUPERIOR GEOLOGY

HELD AT

THE MEAD INN

WISCONSIN RAPIDS, WISCONSIN

MAY 1 AND 2, 1986

ORGANIZED BY THE WISCONSIN GEOLOGICAL
AND NATURAL HISTORY SURVEY

PROGRAM CHAIRMAN AND EDITOR

J. K. GREENBERG

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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.

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 or 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.

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

RECIPIENTS

1979 Sam Goldich
1981 Carl Dutton
1982 Ralph Marsden

1986 G. B. Morey

1983 Burton Boyum
1984 Richard Ojakangas
1985 Paul Sims

INSTITUTE BOARD OF DIRECTORS

- J. K. Greenberg (with B. A. Brown), Wisconsin Geological and Natural History Survey, 3817 Mineral Point Rd., Madison, Wisconsin 53705
- C. E. Blackburn, Resident Geologist, Ministry of Natural Resources, 808 Robertson St., Kenora, Ontario, P9N 3X9
- G. L. LaBerge, Department of Geology, University of Wisconsin-Oshkosh, Oshkosh, Wisconsin 54901
- T. J. Bornhorst, Department of Geology and Geological Engineering, Michigan Technological University, Houghton, Michigan 49931
- D. L. Southwick, Minnesota Geological Survey, 2642 University Ave., St. Paul, Minnesota 55114
- J. Kalliokoski, Department of Geology and Geological Engineering, Michigan Technological University, Houghton, Michigan 49931 (Secretary-Treasurer)

Copies of the Abstracts Volume are available for \$6.00 each
and
Field Trip Guidebooks I and II for \$5.00 each
from

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

LOCAL COMMITTEE

J. K. Greenberg: Conference Chairman and Program
B. A. Brown: Co-Chairman and Treasurer
K. Zwettler: Accounts Administration
R. Juedes: Registration and Publication Sales
T. Evans: Poster Session
K. Massie-Ferch: Field Trip and General Assistance
T. Killeen: Field Trip and General Assistance
All at the Wisconsin Geological and Natural History Survey

BEST STUDENT PAPER COMMITTEE

W. Zwickey, Kimberly Clark Corp., Neenah, WI
R. Anderson, Iowa Geological Survey, Iowa City, IA
K. A. Sverdrup, Department of Geological and Geophysical Sciences,
University of Wisconsin, Milwaukee, WI

GOLDICH MEDAL COMMITTEE

M. M. Kehlenbeck, Department of Geology, Lakehead University, Thunder
Bay, Ont.
W. Bodwell, Resource Exploration, Marquette, MI
K. D. Card, Geological Survey of Canada, Ottawa, Ont.

FIELD TRIP LEADERS

J. K. Greenberg, Wisconsin Geological and Natural History Survey,
Madison, WI
B. A. Brown, Wisconsin Geological and Natural History Survey, Madison, WI
L. G. Medaris, Jr., Department of Geology and Geophysics, University of
Wisconsin, Madison, WI
R. S. Maass, Department of Geology and Geophysics, University of
Wisconsin, Madison, WI

TECHNICAL SESSION CHAIRMEN

- F. R. Luther, Department of Geology, University of Wisconsin,
Whitewater, WI
- D. W. Davis, Department of Geology and Mineralogy, Royal Ontario Museum,
Toronto, Ont.
- D. E. Anderson, Department of Geology, University of Illinois, Urbana, IL
- E. B. Kisvarsanyi, Missouri Geological Survey, Rolla, MO
- C. Craddock, Department of Geology and Geophysics, University of
Wisconsin, Madison, WI
- R. Anderson, Iowa Geological Survey, Iowa City, IA
- C. P. Ervin, Department of Geology, Northern Illinois University,
DeKalb, IL
- W. F. Kean, Department of Geological and Geophysical Sciences,
University of Wisconsin, Milwaukee, WI
- S. W. Bailey, Department of Geology and Geophysics, University of
Wisconsin, Madison, WI

GOLDICH MEDAL RECIPIENT

- G. B. Morey, Minnesota Geological Survey, St. Paul, MN

BANQUET SPEAKER

- J. J. W. Rogers, Department of Geology, University of North Carolina at
Chapel Hill, NC

ACKNOWLEDGMENTS

Certain organizations and individuals have made outstanding contributions to the success of the thirty-second Institute on Lake Superior Geology meeting. We would like to thank Nekoosa Papers Inc. of Port Edwards, WI and Exxon Minerals Co. of Rhineland, WI for their generous financial donations which were allocated as student scholarships and awards for the best student papers. The Stevens Point Brewery of Stevens Point, WI kindly provided a substantial volume of their excellent Point Special beer for the meeting's welcoming party. We would also like to thank the Mead Inn, especially its able executives, June Meyers and Judy Freiman for their very efficient services rendered. A final appreciation goes to various staff members of the Wisconsin Geological and Natural History Survey, including: Kathie Zwettler, Roxanne Miller, and Jerilyn Ruhland for manuscript preparation; Mike Czechanski, Brenda Haskins-Grahn, Deborah Patterson, and Cynthia Leigh for cartographic work in guidebook and map preparation.

OBITUARY

Carl E. Dutton, Age 81, died August 24, 1985, in Madison, Wisconsin after a long illness. Carl was a Research Geologist for 30 years with the United States Geological Survey, specializing in Precambrian investigations. Carl worked cooperatively with the Wisconsin Geological and Natural History Survey on the Geology in northern Wisconsin, with a special emphasis in later years on Vilas County and adjacent areas. One of his many contributions was an analysis of Wisconsin mineral resources. He was born in Dunkirk, Ohio, on January 24, 1904. He received a B.A. Degree from DePauw University in Geology in 1926, a M.S. Degree in 1928 from the University of Illinois and a Ph.D. in 1931, in economic geology from the University of Minnesota. He taught geology at Wayne State University and at the University of Michigan. During World War II he did iron ore research in Upper Michigan. He served on the United Nations Committee on Iron Ore Resources in Geneva in 1953-54 and studied iron deposits in Yugoslavia in 1961 under the auspices of the Aid Program. Carl was a fellow of the Geological Society of America and served as membership secretary for the Society of Economic Geologists. In recognition for his many contributions, he was awarded the Goldich Medal in 1981.

All of us who knew him will miss Carl's good nature and professional integrity.

REPORT OF THE CHAIRMAN

31st INSTITUTE ON LAKE SUPERIOR GEOLOGY

1985

The 31st Annual Institute on Lake Superior Geology was held from May 6-11, 1985, in the Kenora area, Ontario. Technical sessions were held May 8 and 9 at the Inn of the Woods, Kenora. Conference registration was 243, including professional geologists and students. The program consisted of three pre-meeting and three post-meeting field trips, and two days of technical papers.

The one and a half day field trip 1, illustrating the geologic setting and style of gold mineralization in the Lake of the Woods area, led by J.C. Davies, P.M. Smith, and C.E. Blackburn, was run both before and after the meeting, to meet demand. Forty-one and thirty-six participants were registered respectively. A half-day fly-in trip to the Cameron Lake gold property of Nuinsco Resources Limited, appended to the pre-meeting field trip 1, and led by D.R. Melling and D.H. Watkinson, attracted 18 participants. The one-day pre-meeting field trip 2, demonstrating geological relationships in the vicinity of the Wabigoon-Winnipeg River subprovincial boundary near Kenora, led by G.P. Beakhouse, had 35 participants. The one-day post-meeting field trip 3, an interpretation of volcanic facies in the Berry River Formation, near Sioux Narrows, led by G.W. Johns, had 37 participants. The two-day post-meeting field trip 4, demonstrating granitoid related mineralization in the Dryden area, led by F.W. Breaks, R.C. Beard, D.A. Janes, and K.H. Poulsen, had 33 participants.

Technical sessions consisted of 68 papers, 35 presented orally and 33 in the form of posters and rock displays. Thirty eight of the papers were concerned with geological topics in the northern states of the U.S.A., and 30 with topics in Canada. Sixteen student papers were presented. Proceedings of the conference were published in 2 volumes: an abstracts volume, and one guidebook covering all five field trips.

The annual banquet was held on May 8, 1985, and was attended by 161 people. The Goldich Medal was presented to Paul K. Sims by Klaus Schulz. The banquet speaker was Grant Young of the University of Western Ontario who presented a lively talk on his varied, world-wide, "Proterozoic Peregrinations".

Two student paper awards were presented, one each for oral and poster presentations. Jeffrey Vervoort, University of Minnesota-Duluth, received the award for best oral presentation for his paper "Geology of the Jap Lake area of the eastern Vermilion district, northeastern Minnesota", and Wendy Jo Johnson, also of University of Minnesota-Duluth, received the

award for best poster presentation for her paper "The petrology and sedimentation of the Lower Proterozoic Barron Quartzite, northwestern Wisconsin." The awards were presented by Gene La Berge, chairman of the Best Student Paper Committee.

The Board of Directors of the Institute met on May 8, 1985. Members of the Board present at the meeting were: C.E. Blackburn (Chairman), G.L. LaBerge, T.J. Bornhorst, D.L. Southwick, and J. Kalliokoski (Secretary-Treasurer). Invited guests included: R.C. Beard, Bruce Brown, E.D. Frey, Jeff Greenberg, Peter Huddleston, M.M. Kehlenbeck, R.P. Sage, and John Wood. The Board took the following action:

1. Accepted the invitation of Bruce Brown and Jeff Greenberg of the Wisconsin Geological Survey to hold the 1986 meeting at Wisconsin Rapids, Wisconsin.
2. Deliberated on a proposal to hold the 1987 meeting in Minneapolis-St. Paul, in conjunction with the North Central Sectional Meeting of the G.S.A., at the invitation of Peter Huddleston, University of Minnesota-Minneapolis, and a proposal to hold the meeting in Wawa, Ontario, at the invitation of E.D. Frey, R.P. Sage, and John Wood of the Ontario Geological Survey. The Board selected Wawa.
3. Financial standings of the Institute were reviewed by J. Kalliokoski and M.M. Kehlenbeck. Kalliokoski reported that the U.S. account currently contained U.S. \$2,072.88 in savings, and U.S. \$623.00 in the medal account. Kehlenbeck reported that the Canadian account currently contained Can. \$2,753.97.
4. Ken Card, Geological Survey of Canada, was selected, and has subsequently agreed to stand, as replacement on the Goldich Medal Committee for Bill Cannon, who has served three years.

This Chairman wishes to register his pleasure in being involved with the organization of an Institute meeting. Without the co-operation of many people my job would have been impossible. In particular, my friend and colleague, Dick Beard, was invaluable at all times before, during, and after the meeting, handling many minor but important details, and most importantly, attending to financial matters. There were times when we on the local committee wondered if we would cover costs: initially, we needed 100 attendees to break even, hoped for 150, and were amazed when registration reached nearly 250. This was fortunate, because a number of expenses were either under-budgeted, or

forgotten: these were mainly connected with guide-book and abstracts volumes preparation. We therefore echo caution expressed to future chairmen by the previous I.L.S.G. Chairman in preparation and costing of these items in particular.

Respectfully submitted,

A handwritten signature in cursive script, reading "Charlie Blackburn", followed by a horizontal line.

C.E. Blackburn
31 Institute Chairman
Kenora, Ontario
August, 1985

ACTIVITIES AND TECHNICAL PROGRAM

FIELD TRIP I

The Wolf River Batholith and Baraboo Interval
by J. K. Greenberg, B. A. Brown, and L. G. Medaris

Day 1 Tuesday April 29, Rocks of the Wolf River batholith

Day 2 Wednesday April 30, Rocks of the Baraboo interval

32nd I.L.S.G. MEETING MEAD INN, WISCONSIN RAPIDS

WEDNESDAY, APRIL 30

4:00 p.m. - 10:00 p.m.	Registration at the Mead Inn
7:00 p.m. - 10:00 p.m.	Welcoming Party
7:00 p.m.	Presentation of poster displays through 5:00 p.m. May 2.

POSTER PRESENTATIONS:

- C. D. Anderson and D. T. Anderson - Electrical Methods Applied to Gold Exploration, Rice Lake District, Manitoba
- D. T. Anderson - Application of Remote Sensing to a Study of Engineering Terrain Capability Maps in Northwestern Ontario
- S. Bartling and K. A. Sverdrup - Gravity Survey in Southeast South Dakota
- D. M. Davidson - Proterozoic Plate Tectonic Models for the Southern Canadian Shield: Confirmed, Constrained, or Conjectured?
- A. U. Falster - Minerals in Pegmatites of the Wausau Complex, Wisconsin
- J. W. Gell and J. T. Wilband - Petrogenetic Constraints for the Evolution of the Powder Mill Group, Michigan
- R. J. Haefner and J. J. Mancuso - Mississippi Valley Type Mineralization and Dolomitization in the Trenton Formation, Wyandot County, Ohio
- M. A. Jirsa - Iron Formations in the Subsurface of Southwestern Minnesota
- K. Kane and K. A. Sverdrup - Preliminary Magnetic Surveys in Eastern South Dakota
- M. M. Kehlenbeck - Transposed Planar and Linear Fabrics in Rocks of the Heron Bay - Hemlo Supracrustal Sequence

- T. L. Lawler and M. Vadis - Mineral Potential Evaluation of an Iron-Rich Volcanogenic Metasediment, Glen Township, East-Central Minnesota
- *R. S. Maass - Penokean Metamorphism in the Black River Valley, Central Wisconsin: Greenschist to Amphibolite Facies Transition
- T. Mize, W. F. Kean, and K. A. Sverdrup - Magnetic Survey Across the Niagara Fault in Northern Wisconsin
- P. A. Nielsen - Are Komatiites Archean Mantle Plume Products? Hot Spot Origin and Evolution, Archean and Phanerozoic Compared
- K. A. Sverdrup and W. F. Kean - A gravity Survey over the Waukesha Fault in Southeastern Wisconsin
- *M. P. Terry - A Preliminary Study of Regional Metamorphism in Early Proterozoic Rocks Near Mountain, Wisconsin
- J. L. Welsh - A Proposed Fault in Archean Rocks North of Virginia, Minnesota, An Extension of the Biwabik Fault?
- T. Woodzick - Geophysical and Remote-Sensing Characteristics of the Colorado - Wyoming Kimberlite Occurrences

* Asterisk marks those papers eligible for the Best Student Paper Awards.

THURSDAY, MAY 1, 1986

Morning Session - Geochemistry/Petrology

Co-Chairmen: Don Davis and Frank Luther

8:00	Conference Chairman	Welcome
8:01	J.B. Paces and T.J. Bornhorst	Geochemical Cyclicality and Magma Evolution within the Portage Lake Volcanics Flood Basalt Sequence, Upper Michigan
8:20	S.R. Mattson, J.W. Gell, and J.T. Wilband	Chromium-rich Basal Pillow Lavas of the Keweenawan Siemans Creek Formation, Northern Michigan
8:40	G.T. Burgess, J.T. Wilband, and T.A. Vogel	Major and Trace Element Variation within Keweenawan Diabase Dikes of Northern Michigan: Evidence for Magma Mixing and Crystal Fractionation
9:00	K.E. Windom and K.E. Seifert	Does the Layered Mafic/Ultramafic Body Near Matlock, Iowa Represent an Ophiolite or Continental Intrusion?
9:20	J.F. Olmstead, K.E. Windom and K.E. Seifert	Mineralogy and Chemistry of the Ferrodiorite of the Mineral Lake Intrusion, Mellen, Wisconsin
9:40	*K.W. Klewin	The Petrology and Geochemistry of the Potato River Intrusion (Eastern Mellen Complex), Northern Wisconsin
10:00		Coffee Break
10:20	P.M. Whelan	Fiji: The Rise and Fall of an Island Arc--A Modern Analogue to Proterozoic Plate Tectonics in the Lake Superior Region?
10:40	J.K. Greenberg	Igneous Compositions Indicating Progressive Crustal Evolution in the Northern Mid-Continent, U.S.
11:00	*C.K. Lange	Carbon Isotope Systematics in the Lake Superior Region from 1.6 to 2.5 Ga
11:20	*T.J. Boerboom	Early Proterozoic Tourmaline- Bearing Metasedimentary Rocks in Northeastern Todd County, Central Minnesota
11:40	*K. Wilke	The Geology and Petrology of the Garnet-Coloma Area, Garnet Range, Montana.
12:00		Luncheon Buffet and Board of Directors Luncheon

Afternoon Session - Metamorphism/Structure

Co-Chairmen: Dave Anderson and Cam Craddock

- | | | |
|------|---|---|
| 1:20 | C.A. Geiger and
C.V. Guidotti | Precambrian Metamorphism in the
Southern Lake Superior Region: A
Geothermometry and Geobarometry
Study |
| 1:40 | K. Attoh | Metamorphic Pressures, Temperatures
and Early Proterozoic Geotherms in
Northern Michigan |
| 2:00 | P.A. Nielsen | Metamorphism of the Dunbar Gneiss
and Associated Supracrustal Rocks:
NE Wisconsin |
| 2:20 | *D. Schultz-Ela | Strain Models for the Evolution of
the Vermilion District, Minnesota |
| 2:40 | P.J. Carter and
J.C. Palmquist | Strain Analysis of Deformed Archean
Pillow Lavas, Mona Schist,
Marquette County, Northern Michigan |
| 3:00 | | Coffee Break |
| 3:20 | *D.K. Holm | An Account of Multiphase
Deformation During the Penokean
Orogeny: Evidence from the Archean
McGrath Gneiss and Overlying Early
Proterozoic Metasedimentary Rocks
in East-Central Minnesota |
| 3:40 | A.D. Maharidge,
J.J. Mancuso, and
C.M. Onasch | Tectonic Evolution of the Felch
Trough |
| 4:00 | K.N. Plummer and
J.C. Palmquist | Penokean(?) Ductile Shear Zones in
Archean Metadiabase Dikes: Evidence
of Stress Reorientation by Basement
Inhomogeneities, Marquette Range,
Michigan |
| 4:20 | *D.B. Westjohn | A Comparison of Finite Strains in
Quartzites and Slates of the
Marquette Range, Supergroup,
Marquette County, Michigan |
| 4:40 | G.A. Ludvigson and
R.A. Anderson | The Douglas Fault at Amnicon Falls
State Park, Wisconsin: Brittle
Cataclastic textures in Keweenaw
Rocks |
| 6:30 | | Cash Bar |
| 7:30 | | I.L.S.G. Banquet |
| | | - Introductions and Announcements |
| | | - Presentation of Goldich Award to G.B. Morey |
| | | - Guest Speaker - Prof. John J.W. Rogers "The
Precambrian of Peninsular India" |

FRIDAY, MAY 2, 1986

Morning Session - I Special Symposium on the Precambrian
Basement of the North-Central U.S.

Conveners: Ray Anderson and E. B. Kisvarsanyi

8:00	P.K. Sims and Z.E. Peterman	Precambrian Basement Map of the Northern Midcontinent
8:20	B.A. Brown	Problems in the Buried Precambrian of Wisconsin
8:40	J.S. Klasner	Precambrian Basement of the Dakotas and its Relationship to Exposed Precambrian Terrane
9:00	R. Anderson	Review of Iowa Precambrian Geology
9:20	E. Kisvarsanyi and G. Kisvarsanyi	Geology and Metallogeny of Proterozoic Basement Terranes in Missouri
9:40	S.B. Treves	Precambrian Rocks of Nebraska
10:00	W.R. Van Schmus	Precambrian Evolution of the Northern Midcontinent Region
10:20		Coffee Break

Morning Session II - Geophysics

Chairman: C.P. Ervin

10:40	J.E. Nyquist and H.F. Wang	Analysis of a Recent Seismic Reflection and Gravity Profile Across the Midcontinent Rift
11:00	*R. Wunderman	Structure of the Keweenaw Rift and Adjacent Crust from a Magnetelluric Survey in Central Minnesota - Wisconsin
11:20	*C. Ruenger	An Aeromagnetic Study of the Rock Elm Structure - Pierce County, Wisconsin
11:40	P.L. McSwiggen, G.B. Morey, and V.W. Chandler	Gravity and Magnetic Modelling of the Midcontinent Rift System in Minnesota and Adjoining Parts of Wisconsin
12:00		Luncheon Buffet

Afternoon Session - Geophysics/Other Topics

Co-Chairmen: Bill Kean and S.W. Bailey

- | | | |
|------|--|---|
| 1:20 | W.F. Kean | Magnetic Studies of Baraboo Interval (Proterozoic) Rocks from Wisconsin |
| 1:40 | V.W. Chandler | Gravity and Magnetic Anomalies and the Structure of the Central Duluth Complex |
| 2:00 | S.M. Wee,
K. Fujita and
J.T. Wilband | A Gravity Survey of the Lake Michigamme Area, Michigan |
| 2:20 | K.E. Carlson and
V.W. Chandler | A Combined Analysis of Gravity and Magnetic Anomalies in East-Central Minnesota |
| 2:40 | D.W. Davis,
K.H. Poulsen and
S.L. Kamo | Geochronology of the Southern Rainy Lake Area, Northwestern Ontario |
| 3:00 | | Coffee Break |
| 3:20 | C. Boben,
T.J. Bornhorst and
J.L. VanAlstine | Detailed Geological Study of Three Precious Metal Prospects in Marquette County, Michigan |
| 3:40 | R.C. Johnson,
T.J. Bornhorst and
J.L. VanAlstine | Geology and Precious Metal Mineralization of the Silver Creek to Rocking Chair Lakes Area, Marquette County, Michigan |
| 4:00 | A.B. Dickas | Precambrian Stratigraphy Along the Midcontinent Rift Trend. |
| 4:20 | R.A. Paull | Speculations on the Oil and Gas Potential of Keweenawan Midcontinent Rift System in Northwestern Wisconsin |
| 4:40 | J. Kalliokoski | Possible Paleocaliche in Portage Lake Volcanics and the Oronto Group, Northern Michigan |

FIELD TRIP II

Penokean Deformation and Metamorphism in
Central Wisconsin: Volcanic Rocks and Gneisses
by R.S. Maass

DAY 1 Saturday May 3, Wisconsin Rapids to Wausau (overnight)

Day 2 Sunday May 4, end by 3:30 Wisconsin Rapids

ABSTRACTS

Electrical Methods Applied to Gold Exploration,
Rice Lake District, Manitoba

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Considerable exploration activity has centered on the Rice Lake District of Manitoba since the 1920's. More than 250 occurrences of gold mineralization have been delineated, and 4 of these have resulted in gold producers (San Antonio, Central Manitoba, Jeep, Ogama-Rockland, and Gunnar Mines). Activity has been renewed in the area over the last few years because of the higher gold prices. A number of the older areas have been re-examined using newer technology and improved instrumentation.

This study outlined the methods that have been applied to re-examine one of these areas of interest, consisting of VLF, E.M., and airphoto interpretation. Maps have been compiled showing the relationship of the E.M. and photolineaments to geological structures, lithology, and mineralization in the area.

Application of Remote Sensing to a study of Engineering
Terrain Capability Maps in Northwestern Ontario

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For a number of years engineering terrain studies maps have been produced by a combination of airphoto interpretation and ground studies. These maps relate the materials exposed at the surface with the groundwater conditions to give a measure of the suitability of a particular area for sources of engineering materials, for trafficability (roads and railroads, etc.) and for sites for building, etc.

Remote sensing studies have been carried out in an area of northwestern Ontario to deduce the utility of these studies toward producing a map similar to that produced by conventional means. The procedure hinges upon the special sensitivity that the Infrared part of the spectrum has toward the changes in plant vigour associated with changes in the groundwater regime with time.

Landsat computer compatible tapes have been obtained for several dates and a number of algorithms applied to attempt a classification of ground cover type plus an appreciation of change in the spectral reflectivity with time produced by induced senescence. The feasibility map so produced is compared with that produced by conventional means.

REVIEW OF IOWA PRECAMBRIAN GEOLOGY

Raymond Anderson
Iowa Geological Survey

The State of Iowa is located on the southwestern edge of the Superior Province in the north-central U.S. Precambrian rocks are generally overlain by Phanerozoic rocks and unconsolidated Quaternary materials reaching thicknesses in excess of 1.5 km, and are directly known only from two small exposures and 151 drill penetrations. Studies of these samples, in conjunction with interpretations from reasonably good quality gravity and magnetic data from Iowa and the surrounding states, and an ever-increasing understanding of regional Precambrian history, has begun to reveal the history of the Iowa basement.

Rocks encountered in Iowa appear to represent six episodes of Precambrian history. They include plutonism during the Archean Kenoran Orogeny, sediments, volcanics, and a mafic pluton associated with Huronian rifting, metasediments and migmatitic gneiss accreted during the Penokean Orogeny and a late orogenic granitic pluton, Baraboo interval quartzites and metasediments, granites and norites of the Eastern Granite-Rhyolite Terrane, and mafic intrusive and extrusive rocks and clastic sediments associated with the Keweenaw Midcontinent Rift.

The oldest rock known in Iowa is the *Lyon County Gneiss*, a syenitic gneiss encountered in core drilling in northwest Iowa and yielding an age of 2523 ± 5 my (a,1). This rock was apparently intruded into the old (c.a. 3600 my) Archean terrane of the southern Superior Province during the Kenoran Orogeny. The southern margin of the Archean terrane in Iowa is probably coincident with the northeast-trending Storm Lake Trend, best delineated by magnetic anomalies.

Cores from the same area have also penetrated the *Matlock Banded Iron-Formation* associated with a layered mafic pluton and a thick rhyolite, composed of flows and pyroclastics and dated at 2280 ± 110 my (a,1). This sequence is correlated with the earliest Proterozoic rocks of the Huronian Supergroup. Cores and chip samples from northwest and north-central Iowa include the *Camp Quest Gneiss* (a meta-litharenite), the *Harria Granite* (a biotite granite that yielded an age of 1804 ± 17 , a, 3), and the *Manson Migmatite*, all probably associated with the Penokean orogeny (c.a. 1850 my ago). A third sequence of Early Proterozoic rocks present in the northwest part of the state is the Baraboo interval (1760-1630 my) *Sioux Quartzite* and the possibly interbedded *Hull Rhyolite*. Two similar quartzites known from the subsurface of southeast Iowa, near Keota and Cedar Rapids, are probably contemporaneous.

Two Middle Proterozoic plutons associated with the Eastern Granite-Rhyolite Terrane (2) have been encountered in core drilling in Iowa. In the east, the *Green Island Granite*, cored along a northeast-trending belt of positive magnetic anomalies, yielded an age of 1487 ± 15 my (a,3). Chip samples of biotite granites from wells drilled nearby, near Clinton and Dubuque, are probably related. Coring of the Spencer pluton in north-central

Iowa encountered norites and granites that provided minimum ages of about 1300 my (b,4), but may have also been emplaced about 1480 my ago.

The Precambrian of Iowa is dominated by the Keweenawan Rift zone. Both mafic igneous and clastic rocks similar to those exposed in the Lake Superior region have been encountered in drill core and chip samples along the trend of the feature. Igneous samples include the ophitic *Finnegan Gabbro*, a diabase, and the *Thor Basalt* extruded about 1100 my ago and later uplifted with the rift-axial Iowa Horst. Clastic rocks encountered include sandstones, siltstones, and shales.

Additional lithologies known from the Iowa basement include a magnetite-rich peridotite and an olivine gabbro from the northeast, a biotite granite from the southwest, and an alkali granite, the *Hawarden Granite*, from the northwest. The geologic affinities of these rocks is not understood.

a. U/Pb age from zircon

b. Rb/Sr age from biotite

REFERENCES

1. Van Schmus, W. R., Bickford, M. E., and Zietz, I., in press, Early and Middle Proterozoic provinces in the central United States, in A. Kroner (ed), mid-term report for working Group 3, International Lithosphere Program, AGU Geodynamics Series.
2. Bickford, M. E., and Van Schmus, R. W., 1985, Discovery of two Proterozoic, granite-rhyolite terranes in the buried midcontinent basement; Proceedings of the First International Symposium on Continental drilling, Springer-Verlag.
3. Hoppe, W. J., Montgomery, C. W., and Van Schmus, W. R., 1983. Age and significance of Precambrian basement samples from Northern Illinois and adjacent states; J.G.R., v. 88, No. B9, p 7276 - 7286.
4. Lidiak, E. G., Marvin, R. F., Thomas, H. H., and Bass, M. N., 1966. Geochronology of the Midcontinent region, United States, 4. Eastern Area; Jour. Geophy. Research, v. 71, N 22, p 5427-5438.

METAMORPHIC PRESSURES, TEMPERATURES AND EARLY PROTEROZOIC GEOTHERMS IN NORTHERN MICHIGAN

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Metamorphic Conditions

Temperatures (T) of metamorphism of the early Proterozoic Michigamme FM in Peavy, Republic and Watersmeet nodes have been estimated using garnet(GA)-Biotite(BI) geothermometry. In the Peavy node, peak metamorphic conditions which produced sillimanite(SI) - bearing rocks were 560-630°C. Temperatures increase from 500°C at the garnet isograd to 570°C in the staurolite zone consistent with metamorphic grade [1]. Rocks exposed in the sillimanite zone of the Republic node record T of 580-630°C while mineral assemblages in the staurolite zone recrystallized at 550-590°C. In the Watersmeet area, metamorphic T values range from 500°C to 590°C in the garnet zone flanking the northside of the Archean gneiss dome. Biotite gneiss in the dome apparently re-equilibrated at 580°C while Archean age greywacke to the west of the Watersmeet dome gave temperatures of 580-610°C. The maximum pressure(P) recorded by SI-zone rocks in the Peavy Pond area is 4.1kb, an estimate based on the GA-SI-plagioclase(PL)-quartz(QZ) geobarometer. Preliminary estimate of metamorphic P in the Republic node, inferred from andalusite-SI stability field and the GA-muscovite(MS)-PL-BI geobarometer, is 2-3 kb and for the Watersmeet node the P estimate is 6.0 kb. Peak metamorphic T, and P estimates are shown in Fig. 1.

Thermal Models

T, P conditions in the Peavy node have been used to show that localized intrusion heat source could not account for the mapped isograds 1. The subsurface geometry of the isograds inferred from their faulted map pattern and the associated isothermal surfaces, which dip ~40° away from the core of the metamorphic node, indicate an average vertical temperature gradient at 46°C/km [2, 3]. I have calculated the geotherms (temperature-depth curves) in the early Proterozoic crust that would account for the warm temperatures during metamorphism. The data for the calculations include: (i) estimated average radiogenic heat production of 5.59 μWm^{-3} (13.35 hgu) in the Archean crust 2000 Ma ago, (ii) a reduced heat flow and characteristic depth constant of radiogenic heat distribution in the Superior Province crust [4], and (iii) metamorphic P,T data and heat production in early Proterozoic rocks.

In one model I considered accumulation and rapid tectonic thickening (1km/my) of 20-30 km of supercrustal rocks with an estimated radiogenic heat production of 1.88 μWm^{-3} (4.5 hgu) followed by a period of self heating. The geotherm, after being depressed during thickening, relaxes to warmer temperatures, however after 50 my it is still not hot enough to produce the high-T, low-P rocks of Republic and Peavy nodes. For example, the temperature at a depth of 10 km only reaches 450°C. Direct calculation of the warmer, perturbed geotherms from P,T data was carried out for lithosphere thicknesses (ℓ = 60-120 km) and uplift of tectonic pile due to erosion at rate (u = .2-.6km/my) [5]. These geotherms show that regardless of lithosphere parameters considered, the metamorphic P,T data require melting at crustal depths 12-25 km. In particular, the uplift trajectories and associated geotherms of the low-P, high-T Republic node rocks would produce melting of any reasonable composition of the crust at depths less than 12 km.

Implications for Regional Geology and Tectonics

The results of our ongoing metamorphic studies have the following implications with regard to regional geology and tectonics:

- 1) The geobarometric data indicate increase in thickness of the tectonic pile to the south and southwest. This is consistent with the occurrence of kyanite-bearing rocks in the southwestern of the Watersmeet node and provides support for the current hypothesis that a collision zone during the Penokean Orogeny is located to the south of the Peavy metamorphic node.
- 2) Thermal models provide an explanation for the extensive gneiss doming associated with Republic node. The domes represent the diapiric uprise of partial melts of Archean basement produced at shallow levels during the Penokean metamorphic event.
- 3) Post metamorphic uplift rates can be estimated directly from the crustal geotherms and reported hornblende and biotite K/Ar age spectra 6. The estimated uplift rate of 0.05 km/my in the Republic node is 3-4 times higher than the uplift rate of 0.018 km/my in the Peavy node.

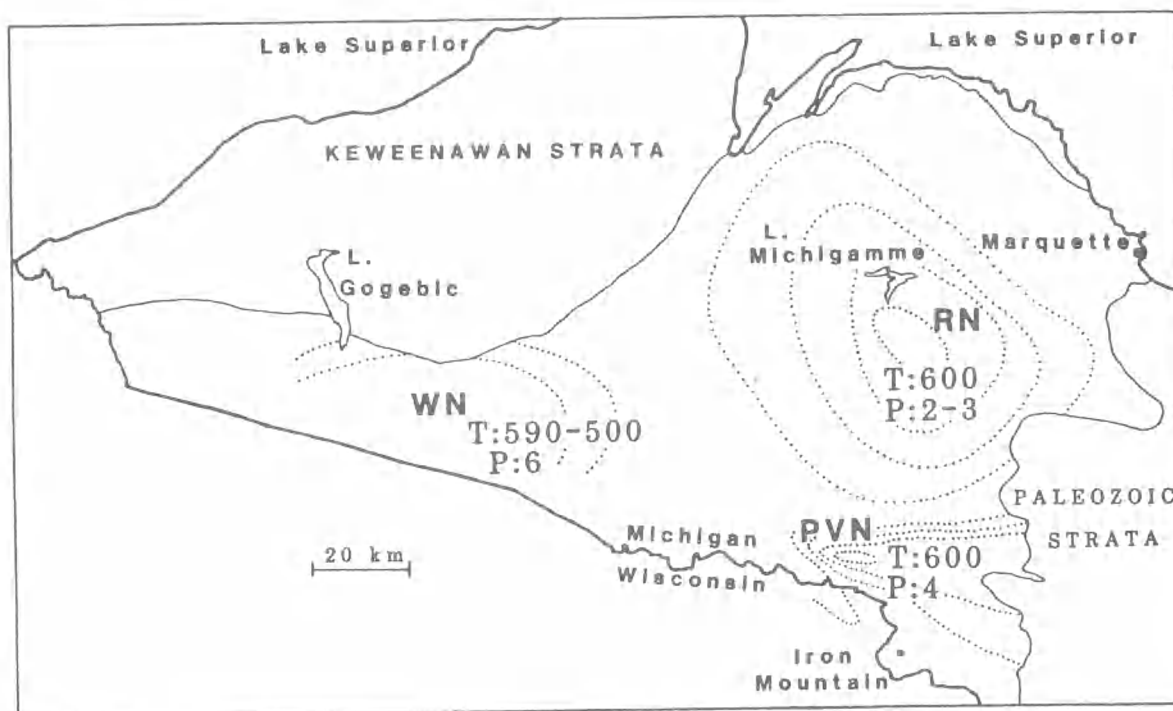


Fig. 1. Peak metamorphic T(°C) and P(kb) in the northern Michigan, metamorphic nodes - PVN (Peavy), RN (Republic), WN (Watersmeet)

References

- 1 Attoh, K. and Vander Meulen, M.J. (1984), Jour. Geol. 91, 417-432.
- 2,3 Attoh, K. (1984), GAC-MAC, London, Ont. and MS in revision.
- 4 Jessop, A.M. and Lewis, T. (1978), Tectonophysics 50, 55-77;
- Lachenbruch, A.H. and Bunker, C.M. (1971), J.G.R., 76, 3852-3860.
- 5 Royden, L. and Hodges, K.V. (1984), J.G.R., 89, 7091-7106.
- 6 Peterman, Z. E. et al (1985), Contrib. Mineral. Petrol. 91, 138-150;
- Winnet, T.L. (1981), M.S. Thesis. Ohio State Univ.

Gravity Survey In Southeast South Dakota

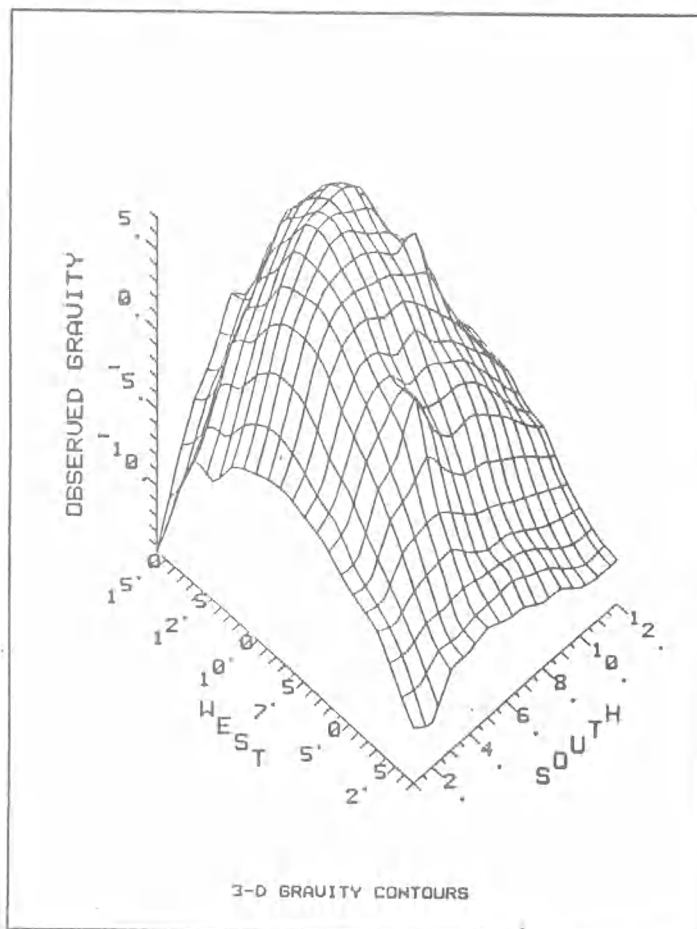
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A gravity survey was conducted in a 670 square mile area in Union, Lincoln, and Minnehaha Counties, South Dakota on a 1 mile square grid. The Bouguer anomaly map produced as a result of the survey shows that the region can be divided into three areas.

To the north there is an ovate gravity high covering roughly 270 square miles with an amplitude of 20 mgals (see the figure below). This feature has a symmetrical N-S gradient of -1.7 mgals/mile away from the peak and an asymmetrical E-W gradient of -3 mgals/mile west and -1.9 mgals/mile east of the peak.

The central section is characterized by a nearly uniform signal with slowly varying values averaging 15 mgals less than the peak to the north.

The southern section is an area of about 150 square miles where there is an increase in gravity values that becomes progressively greater as the southern boundary of the survey area is approached. Within this region the gradient increases from $+1.8$ mgals/mile south to $+5.1$ mgals/mile south. The most rapid increase occurs south of Beresford, South Dakota in Union County. Bouguer anomaly values obtained at the southern boundary of the survey area are roughly 19 mgals above the northern peak.



Detailed Geological Study of Three Precious Metal Prospects
in Marquette County, Michigan

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Three precious metal prospects in Marquette County, Michigan (Bjork Lundeen, Ford and Peppin) were geologically mapped at a scale of 1:200 to 1:100. These areas were chosen because of their varied geologic settings. The data obtained from these three prospects combined with previous studies can provide a base to develop an understanding of the regional geologic setting of precious metal mineralization in northern Michigan.

The Bjork Lundeen prospect is located about 1.0 miles west of Callahan's Ropes Gold Mine. The bedrock consists of variably altered Archean pillowed basalts. Pyrite is found as fine disseminations throughout the basalts and in greater concentrations in association with a northwest-southeast trending quartz vein. An old test shaft and a trench expose parts of the mineralized quartz vein, but geologic relationships in the immediate vicinity are obscure due to the lack of outcrop. Vein quartz contains irregular layers of massive pyrite with intergrown subhedral to euhedral tourmaline and individual euhedral pyrite cubes. Pyrite is also relatively abundant in the adjacent, chlorite altered, country rock.

The Ford prospect is located about 3.1 miles northeast of the Ropes Gold Mine. The bedrock consists of fine-grained clastic Archean sediments cut by two east-west trending, altered, mafic sills. The age of these sills is uncertain, but we suggest that they are Archean. This Archean rock package is unconformably overlain by the Lower Proterozoic Goodrich Quartzite which strikes east-west and dips 65 degrees north. A few very small Keweenaw diabase dikes cut the Archean rocks. The Archean rocks have undergone an intense penetrative deformation exhibited by crenulated and fine anastomosing foliations, folded quartz lenses, and micro and macro faulting. A number of old prospects are located along one of the northwest trending faults which cuts the Archean sediment unit and a mafic sill. This intensely prospected area is centered on closely spaced quartz veins containing variable amounts of pyrite. Pyrite is abundant in the country rock associated with these quartz veins. Carbonate veins were found in a few samples around one of the shafts.

The Peppin prospect is located about 3.5 miles northwest of the Ropes Gold Mine. The bedrock consists of an Archean granodiorite intruded by three felsic dikes and a few aplite dikes. It also contains one mafic unit which is either a dike or a roof pendant. The origin of this mafic unit is unclear because of the sparse outcrops, but it is best explained as a roof pendant. An old shaft was sunk on a 2.5 foot wide quartz vein which is sandwiched between two foliated mafic layers. These mafic layers contain more pyrite than the quartz vein. A trench uncovers another quartz vein which is located at the contact between a sheared felsic dike, a foliated mafic layer, and the granodiorite rock. Pyrite is disseminated throughout the quartz vein and the granodiorite adjacent to the vein. At the trench the granodiorite is altered to potassium feldspar/hematite.

The mineralization at all three prospects is epigenetic and appears to be spatially associated with mafic rocks. Anomalous concentrations of gold are hosted by pyrite-bearing quartz veins, and the localization of these veins is dependent on earlier formed structures. The main non-metallic alteration minerals include quartz, sericite, chlorite, and carbonates.

EARLY PROTEROZOIC TOURMALINE-BEARING METASEDIMENTARY ROCKS
IN NORTHEASTERN TODD COUNTY, CENTRAL MINNESOTA

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Iron-ore exploration in the early 1900's near Philbrook, Minnesota led to a series of thirty-five exploratory core holes. The core was assayed for iron, reduced to 3-10 cm per 2 meters, and stored. In light of the recent interest in Early Proterozoic rocks, this core was exhumed from storage and petrographically examined; five whole rock analyses were obtained to supplement the petrography.

The stratigraphic succession intersected by drilling consists, from bottom to top, of a 90-m section of feldspathic arenite and arkose; a 100-m section of laminated iron-formation, dominantly specular hematite; an 'upper' arkosic and arenitic unit of variable (25-60 m) thickness; and a cap of tourmaline-magnetite-albite-chlorite schist, at least 50 m thick. Thin, stratiform and laterally semicontinuous beds of schist (metabasalt and carbonate-bearing amphibolite), from 2 to 20 m thick, are present throughout the upper three stratigraphic units.

The arkosic rocks are pink-gray and typically strongly sericitized; they contain a few thin intercalated beds, ranging from 0.5 mm to 20 m in thickness, of laminated magnetite-bearing iron-formation. Tourmaline occurs in magnetite-bearing and magnetite-free arkosic rocks as scattered euhedral grains and as thin tourmalinite laminae. The upper chloritic schist also contains abundant laminae and beds of iron-formation, and all gradations between this schist and clastic-rich, magnetite iron-formation are present. Tourmaline is ubiquitous throughout this schist, and is locally concentrated in magnetite-rich laminae. All of the iron-formation contains an abundant clastic component of quartz-feldspar and mica, as impurities in the chemically precipitated rock, and as intercalated clastic-dominated laminae with iron-oxide impurities.

Whole rock analyses of the feldspathic arenite/arkose rocks show a very high $\text{Na}_2\text{O}/(\text{CaO} + \text{K}_2\text{O})$ ratio, due to the predominance of albite in the rock, and rather high Fe values, due to the presence of disseminated magnetite. A whole rock analysis of the mafic metavolcanic shows SiO_2 values comparable with basalt, and high Fe and Mg values. Secondary alteration/metamorphism has greatly altered the alkali values in the metabasalt, with a loss of Ca, Na, and Al, and an increase in K.

The presence of tourmaline and tourmalinite laminae raises interesting questions with regard to both the evolutionary history and economic potential of the rock. Within the past ten years, several authors, including Ethier and Campbell (1977), and Taylor and Slack (1984), have recognized the relatively common association of tourmalinites with a variety of massive-sulfide deposits. These occur mainly in Proterozoic meta-sandstones and pelites, in association with iron-formation and mafic volcanics. The tourmaline of stratiform tourmalinites typically has a lower Fe/Mg ratio than tourmaline of igneous-origin, and also differs from it in

other characteristic minor-element trends. A chemical analysis of Philbrook tourmaline and several other microprobe analyses of individual grains yielded chemical compositions consistent with those of massive sulfide-related stratiform tourmalinites, quite distinct from tourmaline of igneous derivation.

The host rock associations, and the morphological and chemical similarities of the Philbrook tourmalinites to other stratiform tourmalinites, imply an ultimate volcanogenic source from the boron necessary for tourmaline crystallization. Compositional core-to-rim variations and quartz inclusions within grains indicate that the tourmaline originated and/or was enlarged by metamorphic processes from a boron-rich primary sediment.

The associations elsewhere of tourmalinites with massive sulfide deposits imply that a massive sulfide deposit could exist in the Philbrook area.

Ethier, V.G., and Campbell, F.A., 1977, Tourmaline concentrations in Proterozoic sediments of the Southern Cordillera of Canada and their economic significance; *Canadian Journal of Earth Sciences*, v. 14, p. 2348-2363.

Taylor, B.E., and Slack, J.F., 1984, Tourmalines from Appalachian-Caledonian massive sulfide deposits: Textural, chemical, and isotopic relationships; *Economic Geology*, v. 79, p. 1703-1726.

Problems In The Buried Precambrian Of Wisconsin

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In recent years, much effort has been directed at study of the exposed Precambrian rocks in northern Wisconsin. Restudy of the more than 200 wells which penetrate buried Precambrian basement in southern Wisconsin is now underway in an effort to better understand the continuation of outcrop geology into the subsurface.

Eighty percent of available samples are cuttings from municipal and industrial waterwells in the urban areas of southeast Wisconsin, a triangular area defined by Green Bay, Madison, and Milwaukee. The dominant rock types are gray or pink granites, rhyolites, and metasedimentary rocks including quartzite, conglomerate, slate and iron formation. The metasedimentary rocks are correlated with the exposed Baraboo interval metasediments at Baraboo and Waterloo (Brown, 1986). Petrography and limited chemical data suggest that the rhyolites and some of the granites belong to the 1760 Ma suite (Anderson and others, 1980; Smith, 1983). Recent dating of granites from western Wisconsin and from the Madison area (W.R. Van Schmus, unpublished data) suggests that 1500 Ma granites similar to the granite in Stephenson County, Illinois and the Wolf River Batholith occur throughout this region.

Less than twenty samples of basement rocks are available from the entire area from La Crosse northwest to St. Croix falls. Most of these are nondistinctive and often highly weathered granites. Amphibolites of possible volcanic origin from Dunn and Trempealeau Counties suggest a possible westward continuation of Penokean and/or Archean rocks exposed in the Black and Eau Claire River Valleys to the east.

Interpretation of basement geology is limited by the lack of detailed aeromagnetic coverage south of the exposed Precambrian. Regional aeromagnetic maps and the Bouger Gravity Map of Wisconsin (Ervin and Hammer, 1974) define a series of broad northeast trending anomalies in southern Wisconsin. These trends continue to the southwest, and probably represent major crustal features, such as boundaries between Penokean and/or Archean and younger crustal units. In local areas where detailed geophysical surveys have been done, high frequency anomalies are correlatable with shallow basement rocks, such as ferruginous metasediments, and may be discordant with the regional trends.

Rocks at the basement surface in southern Wisconsin and much of Illinois consist of anorogenic granites, rhyolites and sediments ranging from 1480 to 1760 Ma. These rocks may form a veneer overlying older orogenic crust which is reflected in the regional geophysics. Geophysical studies in conjunction with deep drilling are required to determine the nature and age of the basement on which the rhyolites and sediments were deposited. Establishing the extent of crustal formation during the Penokean Orogeny, and the nature of the transition from 1850 Ma orogenic terrane to progressively younger anorogenic terranes to the south is essential to understanding the tectonic evolution of the upper midcontinent region.

- Anderson, J. L., Cullers, R. L., and Van Schmus, W. R., 1980, Anorogenic metaluminous and peraluminous granite plutonism in the mid-Proterozoic of Wisconsin, U.S.A., *Contributions to Mineralogy and Petrology*, v. 74, p. 311-328.
- 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., *Geological Society of America, Memoir 160*, p. 113-128.
- Brown, B. A., 1986, Baraboo interval in Wisconsin, in J. K. Greenberg and B. A. Brown (eds.) *Proterozoic Baraboo interval in Wisconsin*, *Geoscience Wisconsin*, v. 10.
- Ervin, C. P., and Hammer, S., 1974, Bouger Anomaly Gravity map of Wisconsin, Wisconsin Geological and Natural History Survey, Madison, Scale 1:500,000

MAJOR AND TRACE ELEMENT VARIATION WITHIN KEWEENAWAN DIABASE
DIKES OF NORTHERN MICHIGAN: EVIDENCE FOR MAGMA MIXING AND
CRYSTAL FRACTIONATION

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Keweenaw diabase dikes (c. 1 Ga.) intrude Archean basement, Proterozoic metasediments, and Keweenaw lava piles. Of the 55 dikes sampled, 5 exposures in Gogebic county were found to have a positive remnant polarity. They are chemically similar to the negatively polarized, and supposedly older, dike swarms.

A relatively narrow east-west trending band of "high-alumina" dikes, with lower abundances of Ti, P, and the REE, is exposed west of the city of Marquette. These rocks are more primitive, with Mg NUMBERS of 68 to 58, than "low-alumina" dikes exposed on either side of this band and those of the "Gogebic" swarm to the west. In both high- and low-Al types the composition of phenocryst minerals varies markedly from rim to core in some specimens, and the composition of matrix minerals in a few is significantly different from that of the phenocrysts. In general, whole-rock and mineral compositions vary from the chilled margins toward the coarse-grained interiors with the greatest variation observed in the widest dikes. In general this variation is marked by an increase in the REE, alkalis, and Fe and may be the result of in situ crystal fractionation. In some dikes the degree of chemical heterogeneity expressed by the zoned minerals, may have resulted from partial mixing of chemically different magmas. Analysis of 230 grains from 11 specimens have ranges as follows: PLAGIOCLASE An 88-36; OLIVINE Fo 80-41; AUGITE Wo 41-22, En 58-36, Fs 34-9; PIGEONITE Wo 16-12, En 63-53, Fs 24-34.

Chemical modeling of the "high-alumina" dikes based on fractional crystallization of the "chosen parent" mineral compositions determined by microprobe analysis (Fo:83.0, An:88.5, and pyroxene Wo32,En58,Fs10), and using the observed "average" phenocryst proportions of 20% olivine + 20% clinopyroxene + 60% plagioclase from several chilled margins, adequately explains the evolutionary trend of the major and trace elements within the "high-alumina" group. The model assumes that crystal fractionation takes place in increments of 5% and the equilibrium liquidus phases are removed. These same liquidus proportions also yield a subparallel fractional crystallization trend for the "low-alumina" group. The most evolved rocks sampled (south of Cup Lake) can be derived by up to 60% fractional crystallization of the most primitive "low-alumina" parent. Compositions intermediate to these are best explained by mixing compositions of the two trends. We cannot adequately derive the most primitive "low-alumina" basalts from the "high-alumina" basalts without grossly changing the observed liquidus mineral proportions.

A COMBINED ANALYSIS OF GRAVITY AND MAGNETIC ANOMALIES
IN EAST-CENTRAL MINNESOTA

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55114-1057

According to Poisson's theorem, the magnetic potential and the first derivative of the gravitational potential and the first derivative of the gravitational potential are linearly related, with the slope being proportional to the magnetization/density ratio of the source. The relationship remains approximately valid upon first or second differentiation within small windows of anomaly data containing contributions from more than one source. Thus real, multi-source gravity and magnetic data from large areas can be analyzed by applying the theorem in a small moving window that systematically covers the entire data space. The moving window application of Poisson's theorem quantitatively expresses the correlation existing between gravity and magnetic anomalies and yields magnetization-to-density ($dJ/d\rho$) estimates of the sources.

Several improvements were made on moving window Poisson analysis and the method was applied to gridded gravity and magnetic anomaly data over east-central Minnesota. Results in the greenstone-granite terrane show a generally inverse relation along boundaries between greenstone and granite belts, with $dJ/d\rho$ estimates generally between -0.011 and 0.0 units. Within bodies of a given rock type, however, $dJ/d\rho$ estimates commonly range between 0.0 and 0.01021 units; these direct relations reflect the higher densities of the more magnetic phases of the granitic rocks and of the iron-formation-bearing regions in the greenstones. To the south, the Great Lakes tectonic zone (GLTZ) is characterized by excellent, mostly positive correlation, which indicates a consistent relationship between the gravity and magnetic anomalies overlying granitic and alkaline intrusive bodies of presumably Archean age.

Structural troughs of oxide-rich supracrustal rocks in the Cuyuna iron district produce a distinct belt of strongly positive $dJ/d\rho$ estimates which can be traced confidently northeastward from the Cuyuna district into the northern Animikie basin. This suggests that Cuyuna-type troughs and folds may exist 20 to 30 km south of the Mesabi iron range, buried beneath 1 to 3 km of slate and graywacke. The northern margin of this belt of high $dJ/d\rho$ values coincides approximately with the northern limit of cleavage in the Animikie basin and may mark a crustal transition between the stable greenstone-granite terrane to the north and the relatively more mobile gneissic terrane to the south. A sharp curve in the belt may indicate a northwest-striking fault.

In the gneissic terrane, a country rock density of 2.77 to 2.79 g/cm³ was estimated based upon recorded $dJ/d\rho$ estimates over the Freedmen Granodiorite pluton. Positive correlation over this and similar plutonic bodies contrasts with mostly negative correlation to the northeast, where gravity and magnetic anomalies show poor correspondence, and to the southeast, where the Hillman Migmatite comes in contact with the less dense, more magnetic Stearns Granitic Complex.

STRAIN ANALYSIS OF DEFORMED ARCHEAN PILLOW LAVAS, MONA SCHIST, MARQUETTE COUNTY, NORTHERN MICHIGAN, U.S.A.

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Amygdules and pillow shape were utilized to quantify finite strain magnitude and orientation in the pillowed member of the Mona Schist. An orthogonal block was cut from the top of a pillow that contained a large concentration of sub-ellipsoidal amygdules. In the XZ plane the long axes of the amygdules are vertical and strain ratios and initial ellipticities are 2.0 and 1.5 respectively. YZ plane long axes orientation of the amygdules is horizontal N71E. YZ and XY plane strain ratios and initial ellipticities are 1.7 and 1.5 respectively. YZ plane long axes orientation of the pillows is N77E and strain ratios are 1.75-2.0.

The Rf/ϕ method (Dunnett, 1969), the Fry method (Hanna and Fry, 1979), the d-alpha method (Ramsay, 1967), and the long-to-short method (Ramsay, 1967) were applied to the amygdules. The linear intersection technique (Fry, 1979) and the long-to-short method were applied to the pillows. Comparison of data showed good correlation.

The rocks have a well developed foliation, N66E 76NW, which for this study was assumed to be the XY plane. The amygdules were observed to be elongated in the surface - plunging 76/336; this was assumed to be the X-direction. The Z-direction was normal to foliation. After analysis of the data the assumed directions were shown to be incorrect, though close to the measured orientations. The measurements of pillow shape and orientations were taken in an attempt to compare bulk strain of the pillow/Mona system to the strain experienced by the amygdale/pillow system. The comparison is tenuous since using pillows as strain indicators is questionable and the selvages appear to have absorbed some of the strain. Assuming that the Mona responded brittely during middle and late Proterozoic deformational events, the strain measured represents Kenoran or late Archean deformation. The beds appear to have experienced up to 35% shortening in a compressional environment. Others (Burke, Dewey, and Kidd, 1976) have reported that subduction type complexes probably existed in Archean time.

- Burke, K., Dewey, J.F., and Kidd, W.S.F., 1976. Dominance of horizontal movements, arc and microcontinent collisions during the later permobile regime, in *The Early History of the Earth*, Windley, ed., p. 113-129.
- Dunnett, D., 1969. A technique of finite strain analysis using elliptical particles. *Tectonophysics*, 7(2): 117-136.
- Fry, N., 1979. Density distribution techniques and strained length methods for determination of finite strains. *J. of Structural Geology*, 1(3): 221-229.
- Hanna, S.S., and Fry, N., 1979. A comparison of methods of strain determination in rocks from southwest Dyfed (Pembrokeshire) and adjacent areas. *J. of Structural Geology*, 1(2): 155-162.
- Ramsay, J.G., 1967. *The folding and fracturing of rocks*. McGraw-Hill, N.Y., 568 pp.

GRAVITY AND MAGNETIC ANOMALIES AND THE STRUCTURE OF THE CENTRAL DULUTH COMPLEX

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Because of a cover by Pleistocene till, geologic mapping over about 75 percent of the Duluth Complex must rely on geophysical data. Gravity and high-resolution aeromagnetic data have been available over the complex for some time, but direct use of these data for geologic mapping is complicated by strong, regional anomalies that obscure the subtle effect of near-surface geology. The central part of the Duluth Complex was studied, using second vertical derivative (SVD) enhancement of the gravity and magnetic data. The SVD procedure is very effective in attenuating regional anomalies and isolating the effect of localized, near-surface sources.

The SVD gravity and magnetic data reveal that the complex can be divided into several zones of distinctive anomaly signature that grossly outline geologic units (Fig. 1). Zones 1 and 3 delineate the troctolitic units along the base of the complex, and the northern and central subareas of zone 1 correlate with the South Kawishiwi intrusion and Partridge River troctolite, respectively. Zones 2, 4, and 7 correlate with exposures of anorthositic suite rocks. Zone 7 may represent a large, undisturbed remnant of the anorthositic suite "cap" envisioned by Weiblen and Morey (1980). Zone 5, which is sharply characterized by complex, high amplitude SVD magnetic anomalies and a positive SVD gravity anomaly, reflects a poorly exposed troctolitic unit (the Railroad troctolite) that is enriched in wall rock inclusions. The northern prong of zone 6 correlates with the Bald Eagle intrusion, and the configuration of the zone suggests that this funnel-shaped intrusion may continue for about 20 km southward beneath glacial cover. Zone 8 correlates with a ferrogabbro unit exposed along the Erie mining tracks. Several unnumbered zones cannot be presently correlated with any known rock units. Zone 9 (in two parts) is believed to delineate a belt of hornfelsed volcanic rocks.

Zone 10 is characterized by strongly positive gravity and aeromagnetic anomalies and is interpreted to reflect a large belt of dense, magnetic intrusions emplaced into the volcanic roof of the complex. Although exposures are generally poor, several known intrusive bodies lie along this belt, including the Beaver Bay Complex, the Sonju Lake intrusion, a layered troctolite-gabbro sequence near Wilson Lake, and an olivine gabbro near Brule Lake. Anomalies associated with this belt are commonly discordant with the strike of the lavas, and gravity and magnetic studies (Ferderer, 1982) imply steeply dipping contacts. The abundance of anorthosite inclusions of deep-crustal origin in the Beaver Bay Complex implies proximity to an extensive crustal conduit. Although zone 10 is interpreted to be dominated by mafic intrusive rocks, granophyric rocks and disrupted volcanic rocks may be locally abundant. Zone 11 (in two parts) correlates with the undisrupted volcanic rocks along the lakeshore.

Preliminary analysis of gravity and magnetic anomaly lineaments indicate a preference for northwest- and northeast-striking directions for the complex and adjacent terranes. In the Archean rocks northwest of the complex, several northeast- and northwest-striking lineaments can be corre-

lated with Keweenaw diabase dikes and Pre-Keweenaw faults. A diffuse zone of northwest-striking lineaments traverses the entire complex between 47°N.-91°30'W. and 47°30'-92°W. and extends into the Archean terrane. A zone of northeast-striking lineaments in Animikie basin rocks southwest of the Duluth Complex probably reflects Keweenaw diabase dikes that are similar to those exposed southwest of the city of Duluth. The overall pattern of lineaments implies a northeast- and northwest-striking structural control for emplacement of the complex, which at least in part reflects reactivation of Pre-Keweenaw structures.

Ferderer, R.E., 1982, Gravity and magnetic modeling of the southern part of the Duluth Complex, northeastern Minnesota: Unpublished M.A. thesis, Indiana University, Bloomington, Indiana.

Weiblen, P.W., and Morey, G.B., 1980, A summary of the stratigraphy, petrology and structure of the Duluth Complex: American Journal of Science, v. 280-A, p. 88-133.

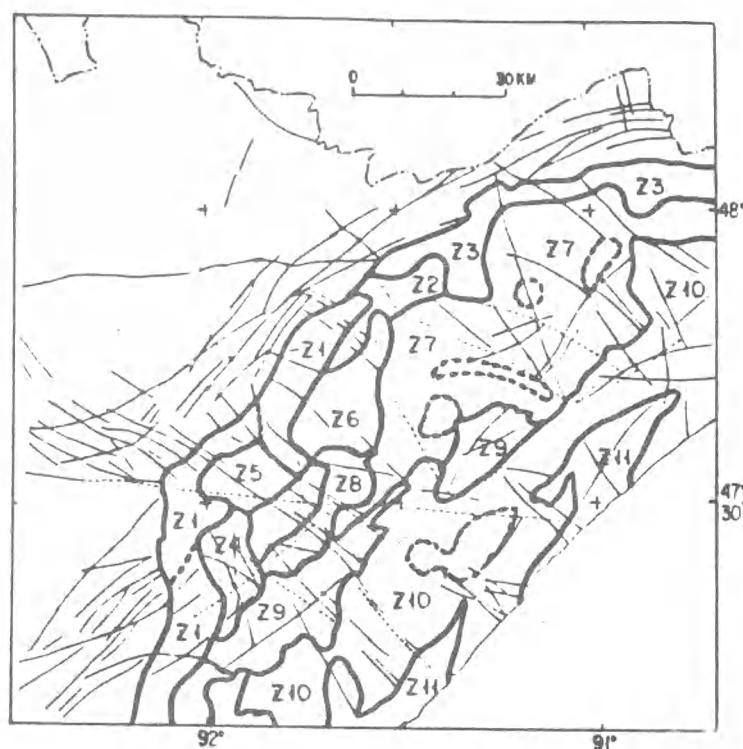


Figure 1. Geologic interpretation of the SVD gravity and magnetic anomaly data. Heavy lines outline zones believed to reflect geologic units. Zones discussed in text are labeled Z1 through Z11. Thin, solid lines represent aeromagnetic anomaly lineaments, whereas thin, dashed lines represent gravity anomaly lineaments.

PROTEROZOIC PLATE TECTONIC MODELS FOR THE SOUTHERN CANADIAN SHIELD:
CONFIRMED, CONSTRAINED, OR CONJECTURED?

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Plate tectonic models have recently been proposed for Proterozoic terranes in the southern Canadian shield, stimulating considerable interest (Holst, 1984; LaBerge and others, 1984; Sims and others, 1985; LaRue and Ueng, 1985). Although initially evolved from paleomagnetic, seismic and oceanographic studies, confirmation of the plate tectonic paradigm for the Phanerozoic has relied heavily on the identification and examination of plate boundaries. The general inability to uniquely define divergent or transform boundaries of Proterozoic age within the southern shield has hampered tectonic analysis, and recent proposals for convergent regimes of that age are only partially documented. Moreover, the lithotectonic assemblages presently observed in Proterozoic terranes can be derived equally well through either vertical (West, 1980) or convergent-plate models (Burke and Dewey, 1973). Thus, the purpose of this paper is to provide a conceptual framework for model assessment and guidance of future research efforts on the subject.

Isotopic age dates as well as the geochemical and lithologic nature (ultramafics; tholeiitic basalts-calc alkaline volcanics; and various plutonic units) of Proterozoic terranes suggest analogs to modern convergent margin assemblages (Schulz, 1984; Sims and others, 1985). However, there are few studies that provide confirmatory evidence of: 1) structures unique to convergent plate regimes (e.g. Holst, 1984; LaRue and Ueng, 1985?), including the nature of structural boundaries between Proterozoic terranes, 2) crustal shortening (Ramsay, 1969; Schwerdtner, 1976), or 3) paleomagnetic control of plates motions.

Thomas and Gibb (1985) have recently proposed that relict convergent boundaries (Proterozoic) can be defined through identification of distinctive, paired Bouguer gravity signatures. Although examples from the Churchill Province will be presented, the author is unaware of such studies in the southern shield.

Numerical model studies of continental deformation in the southern shield may prove useful in evaluating Proterozoic tectonics models through prediction of structural features. Examples of numerical analysis for A-subduction zones have been recently provided by England and McKenzie (1982) for Newtonian and England (unpublished manuscript) for non-Newtonian lithospheric slabs. Although the boundary conditions assumed for such models do not provide detailed analogs for specific orogens, understanding of megascale processes involved in continental deformation can be achieved (Turcotte and Schubert, 1982).

Models involving non-Newtonian lithosphere suggest successive inboard development of: 1) a collision zone with paired Bouguer anomalies, 2) a zone of major strike-separation faults, and 3) a zone of subduction-parallel extension. Possible applications to the southern shield will be discussed as will the constraints, particularly lithospheric thickness, which are inherent in such models

REFERENCES

- England, P. and McKenzie, D., 1982, A thin viscous sheet model for continental deformation: *Geophys. J.R. Astr. Soc.* v. 70, p.295-321.
- Holst, T.B., 1984, Evidence for nappe development during the early Proterozoic Penokian Orogeny, Minnesota: *Geology*, v. 12, p.135-138.
- LaBerge, G.L., Schluz, K.J., and Myers, P.E., 1984, The plate tectonic history of north-central Wisconsin: Thirtieth Annual Institute on Lake Superior Geology, Abstracts with Programs, p.25-27.
- Larue, D.K. and Ueng, W.L., 1985, Forence-Niagara terrane: an early Proterozoic accretionary complex, Lake Superior region, USA: *Geol. Soc. Amer. Bull.* v. 96, p.1179-1187.
- Ramsay, J.G., 1969, The measurement of strain and displacement in orogenic belts: *Geol. Soc. London Spec. Pub.* 3, p.43-79.
- Schulz, K.J., 1984, Volcanic rocks of northeastern Wisconsin: Thirtieth Annual Institute on Lake Superior Geology, Guide to Field Trip No. 1, p.51-93.
- Schwerdtner, W.N., 1976, A principle difficulty of proving crustal shortening in Precambrian shields: *Tectonophysics*, v. 30, T19-T23.
- Sims, P.K., Peterman, Z.E., and Schulz, K.J., 1985, The Dunbar Gneiss-Granitoid Dome: implications for early Proterozoic tectonic evolution of northern Wisconsin: *Geol. Soc. Amer. Bull.*, v. 96, p.1101-1112.
- Thomas, M.D. and Gibb, R.A., 1985, Proterozoic Plate subduction and collision: processes for reactivation of Archean crust in the Churchill Province: in *Evolution of Archean Suprocrustal Sequences* (Ayres, L.D. and others, ed.): *Geol. Assoc. Canada Special Paper* 28, p.263-279.
- Turcotte, D.L., and Schubert, G., 1982, *Geodynamics*: John Wiley and Sons, New York, 449p. (chapters 7 and 9 are of particular interest)
- West, G.F., 1980, Formation of continental crust: in *The Continental Crust and its Mineral Deposits* (Strangway, D.W., ed.): *Geol. Assoc. Canada Special Paper* 20, p.117-148.

GEOCHRONOLOGY OF THE SOUTHERN RAINY LAKE AREA, NORTHWESTERN ONTARIO

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The southern Rainy Lake area forms a wedge-shaped Archean terrain separated from the Wabigoon subprovince to the north by the Quetico fault and the Quetico subprovince to the south by the Seine River - Rainy Lake fault. Geological relationships here have been a source of controversy since the early studies of A.C. Lawson (1913). The area can be divided into a number of different lithostratigraphic domains on the basis of structure. U-Pb zircon ages have been measured for 6 rocks in different domains in order to determine their time relationships and to help resolve some of the controversies associated with this area.

The age of a probable metavolcanic rock from the core of the Rice Bay dome is 2723 ± 3 Ma. A sample of a quartz porphyry sill intruded into Coutchiching sediments at Bear Pass, near the margin of the dome, yields a complex zircon population which defines a mixing line with a lower intersection of 2752 ± 25 Ma and an upper intersection of 4300 ± 700 Ma. The lower intersection is considered to be the age of intrusion of the sill. The upper intersection, although very imprecise, indicates inheritance from a much older crustal source. All zircons in this sample are resorbed, suggesting that they have been derived from partial melting of an underlying basement.

The age relationship between the sill and the rhyolite at the core of the dome is consistent with structural studies by Poulsen et al. (1980), who argued that the Rice Bay dome was formed within an inverted stratigraphic sequence. The age from the core of the dome is a maximum for inversion and doming, while both metasedimentary and metavolcanic rocks surrounding the dome must be older than 2752 ± 25 Ma.

The age of a trondhjemite sill within the Bad Vermilion Lake intrusion is 2729 ± 3 Ma, similar to the age of 2728 ± 5 Ma measured from overlying rhyolite. These sills may therefore represent subvolcanic magma chambers for rhyolite magmatism. A trondhjemite clast from the Seine conglomerate gives an age of 2695 ± 3 Ma. This is a maximum age for the Seine Group. A minimum age for the end of regional deformation is given by emplacement of the Ottertail stock at 2686 ± 1 Ma. Deposition and deformation of the Seine Group is therefore tightly bracketed within a period of 9 ± 4 Ma. In addition, the Seine Group is shown to be distinctly younger than the Coutchiching Group. If the Quetico metasediments, which make up a large part of the Quetico subprovince to the south, are correlative with the Coutchiching Group, then the Seine Group cannot be their lateral facies equivalent, as has been proposed elsewhere (Mackasey et al., 1974). Support for this is given by data of Percival (1986), who also dated a clast from the boundary between the Wabigoon and

Quetico subprovinces, west of Lake Nipigon. His age agrees within error with the age of our clast, showing that late deposition of conglomerate was probably contemporaneous along the subprovince boundary.

Since the Seine Group lies with angular discordance upon older "Keewatin" age volcanics and plutons, and is itself deformed, the area must have been affected by at least two deformational events. The earlier one is bracketed between 2723 Ma and 2695 Ma and is probably correlative with the late deformational event which affected the Wabigoon subprovince to the north (Davis and Edwards, 1985).

Corfu and Stott (1985) have determined ages for deposition and deformation of a Timiskaming-type sequence in the Shebandowan subprovince. These ages agree within error with those bracketing the Seine Group. On the basis of field relations and age, therefore, the Seine Group may be considered a Timiskaming-type sequence. Both deposition and deformation of the Seine Group may have been the result of late isostatic adjustments localized along major transcurrent fault systems and associated wrench zones which separate the Wabigoon and Quetico subprovinces (Poulsen, 1986).

Corfu, F., and Stott, G.M. 1985. U-Pb geochronology and tectonic history of the Shebandowan belt, northwest Ontario. Abstract, 31st annual meeting, Institute on Lake Superior Geology, Kenora, Ontario pp.15-16.

Davis, D.W., and Edwards, G.R. 1985. Evolution of an Archean igneous complex from high precision U-Pb data: the Kakagi Lake area, N.W. Ontario. Abstract, 31st annual meeting, Institute on Lake Superior Geology, Kenora, Ontario pp.20-21.

Lawson, A.C. 1913. The Archean geology of Rainy Lake re-studied. Geological Survey of Canada, Memoir 40. 111 p.

Mackasey, W.D., Blackburn, C.E., and Trowell, N.F. 1974. Ontario Division of Mines, Miscellaneous Publication 58, 30 p.

Percival, J.A., and Sullivan, R.W. 1986. Age constraints on the evolution of the Quetico Belt, Superior Province, Ontario. Abstract, Workshop on the Tectonic Evolution of Greenstone Belts, Lunar and Planetary Institute, January 16-18, Houston, Texas, pp.91-93.

Poulsen, K.H. 1986. Rainy lake wrench zone: an example of an Archean subprovince boundary in northwestern Ontario. Abstract, Workshop on the Tectonic Evolution of Greenstone Belts, Lunar and Planetary Institute, January 16-18, Houston, Texas, pp.97-99.

Poulsen, K.H., Borradaile, G.J., and Kehlenbeck, M.M. 1980. An inverted Archean succession at Rainy Lake, Ontario. Canadian Journal of Earth Sciences, 17, pp.1358-1369.

PRECAMBRIAN STRATIGRAPHY ALONG THE MIDCONTINENT RIFT TREND

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In 1983 northern Wisconsin became a target for hydrocarbon leasing agents. This region is better known for Duluth gabbro than oil or gas. The column of interest is the 7620+ m thick clastic sequence termed the Keweenawan Supergroup, a basal shale of which has been Rb-Sr age dated 1.047 ± 50 billion years. Within the past decade this sequence has been recognized as having been deposited in response to tensional processes resulting in a rift system. This Midcontinent Rift is best outlined by gravity and can be traced from the Keweenawan Peninsula of Michigan across northern Wisconsin, Minnesota, Iowa and Nebraska into northeastern Kansas, a distance of 1,300 km.

An organic shale source unit is known in the area, where it creates subsurface oil seeps in the White Pine mine of Michigan. To the southwest along the trend of the rift, the extent of Keweenawan equivalent sediments are masked by Paleozoic and younger sediments. In the mid-1960's a natural gas storage drilling program centered on Dakota County, Minnesota cored extensive thicknesses of Precambrian clastics, subsequently named the Solor Church Formation. This subsurface unit, together with exposures of the younger Hinckley Sandstone and Fond du Lac Formation, constitutes the Keweenawan section of Minnesota. Less is known of the Keweenawan lithology of Iowa, where Minnesota terminology is utilized in geophysical studies of the Midcontinent High. Here a late Precambrian "red clastic" sequence is known, similar to that termed the Rice Formation in Kansas; a carbonate subordinate sequence of sandy shales and feldspathic sandstones.

MINERALS IN PEGMATITES OF THE WAUSAU COMPLEX WISCONSIN

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The miarolitic cavities in pegmatites of the Wausau Complex yield, besides the rock forming minerals quartz, feldspars, amphiboles, micas, etc., an astonishing array of accessory minerals. Typical examples are mineral species bearing iron, titanium, beryllium, rare earth elements, and zirconium.

Several typical assemblages in the four major pegmatite types can be distinguished:

a) simple paragenesis of small pegmatite bodies with primary miarolitic cavities:

Hematite, hisingerite, phenakite, bertrandite, siderite (typically replaced by other iron minerals), anatase and rarely others are common accessories.

b) large complex pegmatites with primary miarolitic cavities:

Pyrite, jamesonite, and other sulfides and sulfosalts, siderite (replaced), phenakite, bertrandite, bavenite, anatase, rutile, zircon, fluorite, fluorapatite, cheralite, jarosite, hematite, ilmenite are typical accessory minerals for this pegmatite type.

c) simple pegmatites with many tiny primary miarolitic cavities:

Hematite (dominant), pyrite, zircon, monazite, fluorite, fluorapatite are typical examples.

d) secondary miarolitic zones in solution-etched pegmatites:

Anatase, rutile, brookite, ilmenite, cheralite, zircon, hematite, xenotime, monazite are examples of accessory minerals encountered in this type of pegmatite.

Precambrian Metamorphism in the Southern Lake Superior Region:
A Geothermometry and Geobarometry Study

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The southern Lake Superior area constitutes the southern extension of the Precambrian Canadian craton. It has experienced a long and varied geologic history encompassing repeated tectonic and metamorphic events beginning around 3.8-3.6 Ga ago and ending around 1.1 Ga. In general the various events have produced a polymetamorphic terrane, but certain areas record single and isochronological metamorphic events. We have undertaken a regional geothermometry and geobarometry study of this area and attempted to document the style of metamorphism for the several events.

Two contrasting Archean-aged geologic terranes are present (Sims, 1980). One is an older southern gneiss terrane which has parts as old as 3.8-3.6 Ga. It is polymetamorphic, recording region-wide Archean events at 3.1, 2.6, and Proterozoic events at 1.8, and 1.6 Ga ago. The second, more northern "granite-greenstone" terrane was generated 2.75 to 2.6 Ga and has not been as strongly effected by later metamorphic events.

Archean metamorphism(s) in the gneiss terrane was relatively high grade, with $P = 5$ to 6 Kb and $T = 650$ to 850°C , with selected areas reaching the orthopyroxene isograd (Central Minnesota and the Minnesota River Valley, Darce and others, 1984; Himmelberg and Phinney, 1967). In central Wisconsin orthopyroxene is absent but migmatites are present (Van Schmus and Anderson, 1977). In contrast, the metamorphic intensity of the "granite-greenstone" terrane was lower with $P < 3$ Kb and $T < 450^{\circ}\text{C}$. It is possible that late Archean metamorphism in the "gneiss" terrane can be related to a collisional event with the more northern "granite-greenstone" terrane.

P and T estimates indicate that by the end of the Archean a relatively thick and largely sialic crust had developed. Average metamorphic geotherms for late-Archean metamorphism using peak conditions are approximately $35^{\circ}\text{C}/\text{Km}$ ($P = 6$ Kb and $T = 675^{\circ}\text{C}$). This is similar to other regionally metamorphosed Archean terranes.

The most extensive Proterozoic regional metamorphic event, especially in Wisconsin, is related to the Penokean orogeny of 1.8 Ga. Penokean metamorphism mainly occurred in the low pressure to intermediate-low pressure ($P \leq 4$ Kb) facies series as defined by Miyashiro (1973), except for small areas of intermediate pressure facies series ($P \sim 7.5$ Kb) kyanite

schists in northern Wisconsin. The highest grade attained was the lower sillimanite zone, but much of the metamorphism was lower grade and reached only the greenschist facies. Metamorphism was in a general sense contemporaneous to the major deformational activity. It is proposed that Penokean metamorphism can be explained in a plate-tectonic context. The source of heat for metamorphism is not agreed upon. James (1955) postulated buried intrusives to account for the nodal pattern of metamorphism in Michigan. We propose that crustal thickening during collision with possible crustal underplating and injection by mafic melts promoted metamorphism.

Radiometric age-dates of a variety of types, Rb-Sr, U-Pb, and K-Ar, indicate complicated post-Penokean tectonic and metamorphic activity. Low grade metamorphism occurred around 1.63 Ga, but its cause is uncertain. Some workers have called upon regional uplift and flexure to account for this metamorphism and the accompanying radiometric resets. Other workers feel it is related to plate subduction that occurred to the south (Dott, 1983). The interpretation is complicated by metamorphic effects associated with intrusion of Wolf River type plutons around 1.5-1.45 Ga. This is especially true in southern and central Wisconsin where possibly widespread contact-like metamorphism affected supracrustal sediments. Suggested metamorphic conditions are $P < 3.8$ Kb for the Waterloo and Baraboo Quartzites but, temperature may have been up to 200°C higher at Waterloo ($T \sim 550^\circ\text{C}$) than at Baraboo ($T \sim 350^\circ\text{C}$). Two metamorphic events have been documented in the Waterloo area with an ^{39}Ar - ^{40}Ar hornblende age-date giving a good plateau at 1.44 Ga.

References

- Dacre, G. A., Himmelberg, G. R., and Morey, G. B., 1984, Pre-Penokean igneous and metamorphic rocks, Benton and Stearns counties Central Minnesota: Rep. of Invest. 31, Minn. Geol. Sur., 16 pp.
- Dott, R. H., Jr., 1983, The Proterozoic red quartzite enigma in the north-central United States: Resolved by plate collision?: Geol. Soc. Am. Memoir 160, Medaris, L. G. Jr., ed., pp. 129-141.
- Himmelberg, G. R., and Phinney, W. C., 1967, Granulite facies metamorphism, Granite Falls-Montevideo area, Minnesota: Jour. Petrol., v. 8, pp. 325-348.
- James, H. L., 1955, Zones of regional metamorphism in the Precambrian of northern Michigan: Geol. Soc. Am. Bull., v. 66, pp. 1455-1488.
- Miyashiro, A., 1973, Metamorphism and Metamorphic Belts: George Allen and Unwin Ltd., London, 492 pp.
- Sims, P. K., 1980, Boundary between Archean greenstone and gneiss terranes in northern Wisconsin and Michigan: Geol. Soc. Am. Spec. Pap. 182, Morey, G. B. and Hansen, G. N. eds., pp. 139-146.
- Van Schmus, W. R., and Anderson, J. L., 1977, Gneiss and migmatite of Archean age in the Precambrian basement of central Wisconsin: Geology, v. 5, pp. 45-48.

PETROGENETIC CONSTRAINTS FOR THE EVOLUTION OF THE POWDER MILL GROUP,
MICHIGAN

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The Keweenawan age Powder Mill Group (PMG) represents the first lavas to be extruded during the development of the Midcontinent Rift in Upper Michigan. The lavas are continental quartz tholeiites, olivine tholeiites, andesites, with felsites in the uppermost part of the section. Preliminary isotope work on the PMG yielded a single isochron with an initial $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.7043 ± 0.0003 and an age of 1209 ± 36 Ma.

Investigators of the Keweenawan igneous suite and continental tholeiites elsewhere in the geologic column have identified a chemical duality of magma types: high and low TiO_2 , P_2O_5 , and REE. This dichotomy has been attributed to fractional crystallization, magma residence time, different mantle sources, and crustal contamination. Variation in Rb-Sr isotopes and trace element data have been interpreted to suggest different mantle sources for the Keweenawan Portage Lake Lavas. However, the PMG and associated dike swarms present a continuous trend of MgO and incompatible elements indicative of fractional crystallization from a single source. These patterns distinguish the PMG from other plateau lavas and related subvolcanic rocks associated with Midcontinent rifting.

Major and selected trace element data show an evolving path for the PMG lavas. While SiO_2 varies little in the tholeiites and andesites, there are significant variations in MgO, CaO, FeO, and Al_2O_3 . The positive correlation of Sr/Rb with MgO is interpreted to mean that the variation of lava types is not a result of crustal contamination. Chemical variations can be modeled by crystal fractionation of olivine, augite, and smaller amounts of plagioclase.

Igneous Compositions Indicating Progressive Crustal
Evolution in the Northern Mid-Continent U.S.

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Proterozoic and younger crustal regions marginal to Archean cratons typically undergo a progressive maturation. The idealized scenario of maturation involves one or more major episodes of accretion onto a nucleus of Archean crust. This accretionary stage may be envisioned as an analogue of Phanerozoic plate collisional tectonics or as some more epeirogenic phenomenon (Greenberg and Brown, 1983; Hermes and Borradaile, 1985). Unless interrupted by successful plate rifting and later convergent orogeny, there follows a very long period of relative stability during which the "new" continental sial thickens and is generally only affected by anorogenic magmatism. In many worldwide examples the anorogenic stage has been interrupted by subsequent orogenic periods. In many other cases including the northern mid-continent, the anorogenic development has prevailed for over 1.5 b.y.

Igneous rock compositions, particularly volcanic, have been interpreted in various ways as indicators of tectonic environment. It was previously sufficient just to distinguish between magmatic suites representing orogeny from those that are anorogenic. With a growing bank of compositional data and a better understanding of the relationship between plutons and tectonics (Michot and others, 1984; Pierce and others, 1984) interpretation is becoming more sophisticated. It is now often possible to resolve even subtle differences in tectonic environment within Precambrian terranes.

Changes in maturing continental crust are reflected in the various products of anorogenic magmatism which were generated by processes including reactivation of zones of structural weakness (such as sutures or other major tectonic boundaries). Through time, melting is initiated in or below progressively thicker sial; crystallization as well as fusion occur at potentially deeper levels. Longer potential residence times for melts in the crust increase the likelihood of wallrock and multiple-magma interaction (contamination, mixing, etc.) Older crust and mantle materials of diverse composition (trace elements, isotopic characteristics, volatiles, etc.) may become increasingly available as magma sources. Along with these changes there is also a greater relative stability and healing of structural weaknesses which attend the progressive crustal thickening. Stability may increase because there is a greater volume of rock to affect thermally and older regions are typically further from stresses generated at plate margins. This probably explains why the latest anorogenic plutons in a region are often volumetrically minor and localized along linear trends. So, for apparently equivalent regions under "stable" anorogenic conditions different types of magmas may be produced depending on the span of time elapsed since original cratonization (post accretion).

In the southern Lake Superior region compositions of Penokean (ca. 1900 to 1820 Ma) volcanic and plutonic rocks indicate that a southern arc-related complex of igneous suites was accreted onto a previously rifted Archean

continental margin on the north (Greenberg and Brown, 1983; Schulz, 1984). Schulz (1984) has also found that both Penokean and post-orogenic 1760 Ma granitic rocks in Wisconsin vary compositionally depending upon their location. Variations in Penokean plutons may be related to subduction polarity during orogeny. Those 1760 Ma plutons closer to the Archean craton in northern Wisconsin are typically more calcalkaline, whereas those in southern Wisconsin associated with 1760 Ma rhyolites are epizonal anorogenic bodies with higher Fe:Mg and alkali:Ca ratios. Granitic rocks of roughly equivalent age (ca. 1750-1850 Ma) in Minnesota are also more calcalkaline, like the Amberg, Radisson, and Jones Creek 1760 Ma plutons in northern Wisconsin.

After the Penokean orogenic period, magma types in the region evolved from relatively simple to more complex. Although the 1760 and 1500 Ma episodes of anorogenic magmatism produced similar types of granites in approximately the same area, the later episode was more complex. At 1760 Ma, perhaps in a basin-and-range type environment, granite (initial Sr isotopic ratio .705) was almost exclusively the only compositional type generated. Anorthosite, mangerite, and both quartz and silica-undersaturated syenite (Sr initial ratio .702) accompanied texturally diverse granites (Sr initial ratios .705 - .710) at 1500 Ma. At about the same time (ca. 1450 Ma) granite and rhyolite similar to those of the 1760 Ma episode in Wisconsin were generated in less mature continental sial 200 to 1000 km south, presumably nearer to the contemporary continental margin. Thermal conditions prevailing at around 1760 and 1500 Ma may have been expressed in either uplift, local crustal thinning or both. The overall stress regime was probably tensional to neutral (Emslie, 1978). Later (ca. 1200 Ma), with presumably still more evolved continental sial and without evidence of major uplift in the region, the Keweenawan rift system produced complex high-Fe magmatic suites. Earlier Keweenawan lavas were notably potassic. A later high-Al tholeiitic series reflected a more advanced state of rift development. Keweenawan alkaline and tholeiitic intrusions are exposed from southern Canada into northern Minnesota and Wisconsin (Weiblen, 1982). Extreme compositional diversity marked this latest episode of Proterozoic anorogenesis.

Kimberlite diatremes are evidence of the final, very minor tapping of the mantle for magmas in this part of North America during the Paleozoic. By Paleozoic time the vertical growth of the continent was such that significant uplift and subsidence were still occurring but with little reactivation of structural weaknesses.

The southern Lake Superior region does not represent a unique case of Proterozoic crustal evolution. The Guiana shield area of Venezuela had the same sequence of magmatic episodes. Both the rock types produced and the times of magmatic activity parallel those in Wisconsin. The Nubian shield area in Egypt is a younger Proterozoic (ca. 1200 Ma to Tertiary) analogue of the North American example. In each of these cited examples Proterozoic or later sial developed through time after a preceding orogenic accretionary period. Isotopic data suggest cratonization of Proterozoic terranes within about 100 m.y. after orogeny. Earliest anorogenic melts were typically derived from relatively shallow-level non-continental basement rocks and from minor reworking of older craton.

References Cited

- Emslie, R.F., 1978, Anorthosite massifs, rapakivi granites, and late Proterozoic rifting of North America: *Precamb. Res.*, v. 7, p. 61-98.
- Greenberg, J.K. and Brown, B.A., 1983, Lower Proterozoic volcanic rocks and their setting in the southern Lake Superior district: *Geol. Soc. of America Memoir* 160, p. 67-84.
- Hermes, J.J. and Borradaile, G.J., 1985, On orogeny and epeirogeny in the study of Phanerozoic and Archean rocks: *Geoscience Canada*, v. 12, p. 148-151.
- Michot, J., Weis, D., and Demaiffe, D., 1984, The granitic rocks and the development of the continental crust: *Ann. Soc. Geol. Belgium*, v. 107, p. 15-25.
- Pearce, J.A., Harris, N.B.W., and Tindle, A.G., 1984, Trace element discrimination diagrams for the tectonic interpretation of granitic rocks: *Jour. Petrology*, v. 25, p. 956-983.
- Schulz, K.J., 1984, Early Proterozoic Penokean igneous rocks of the Lake Superior region: geochemistry and tectonic implications: (abs.) 30th *Ann. Inst. on Lake Superior Geol.*, Wausau, p. 65-66.
- Weiblen, P.W., 1982, Keweenawan intrusive igneous rocks: *Geol. Soc. of America Memoir* 156, p. 57-82.

Mississippi Valley Type Mineralization and
Dolomitization in the Trenton Formation, Wyandot
County, Ohio

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Trace amounts of sphalerite, pyrite and marcasite along with abundant saddle and replacement dolomite and sparry calcite were examined in nine drill holes along a fracture zone in the Ordovician Trenton Formation in Wyandot County, Ohio. The Wyandot fracture zone consists of a series of anastomosing fractures whose overall trend is N 30° W and length is at least eight miles.

The paragenetic sequence of mineralization as observed from the wall of the fracture is: 1) pyrite, marcasite and saddle dolomite, 2) sphalerite, 3) coarse sparry calcite (commonly with inclusions of liquid hydrocarbons), and 4) anhydrite and gypsum. Fluid inclusion data from dolomite, sphalerite and calcite indicate that these fracture-filling minerals were precipitated from warm, saline (approx. 14.8-22.9 wt. % NaCl) brines. The decrease in homogenization temperature (mean values for dolomite = 99.1° C, sphalerite = 82.9° C and calcite = 60.1° C) indicates that the temperature of the solutions progressively decreased during precipitation.

Petrographic and cathode luminescence analyses reveal compositional zonation in dolomite and calcite. The zones are most easily explained by the mixing of fluids. Geochemical constraints limit the transport of metals and sulfide in the same solution; therefore, sulfide precipitation most likely resulted from mixing of two fluids— a warm brine carrying metals and a fluid bearing liquid hydrocarbons and H₂S.

We conclude that the paucity of zinc mineralization in the Wyandot fracture zone in the Trenton Formation is attributed to poor timing. Sulfur (as H₂S) was not available in sufficient quantities at the time the metal-bearing brines arrived in the fracture since the calcite which hosts hydrocarbon inclusions postdates the sphalerite mineralization.

An account of multiphase deformation during the Penokean orogeny: evidence from analysis of the Archean McGrath Gneiss and overlying Early Proterozoic metasedimentary rocks in east-central Minnesota.

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The Archean McGrath Gneiss and overlying Early Proterozoic Denham Formation have undergone similar conditions of deformation related to the Penokean orogeny. Petrographic analysis indicates dominantly ductile deformation involving crystal-plastic processes under moderate-high temperature/moderate pressure external conditions. The McGrath Gneiss has a poorly developed to extremely well developed east-west foliation and horizontal lineation. Minor anastomosing shear zones crosscut the foliation.

The Denham Formation comprises a variety of rock types (quartzite, marble, schist, metaarkose, pillow basalts, and volcanoclastic rocks) and directly overlies the McGrath Gneiss. Complex deformation involved the formation of a pervasive bedding-subparallel foliation similar to that of the overlying Thomson Formation. Late east-west trending folds have axial surfaces that dip steeply to the north and south. An east-west, horizontal mineral lineation is also pervasive throughout the Denham Formation.

The Denham Formation has been metamorphosed to the staurolite zone of the amphibolite facies. The peak metamorphic temperature occurred immediately(?) after the formation of the later structures. Biotite-garnet geothermometry give temperature conditions associated with the later deformation of ca. 530°C. Almandine composition gives pressure conditions on the order of 4.5 kb.

The rocks of the Denham Formation (and its probable correlative, the Chocoma Group) are interpreted as shelf deposits formed during rifting.¹ Rifting was localized by a preexisting zone of weakness-the Great Lakes tectonic zone. The distribution of early Proterozoic bedded rocks indicates that rifting ended to the west in the Lake Superior region.²

Extension was followed by the Penokean orogeny and involved subduction of the more stable granite-greenstone terrane beneath the gneissic craton to the south. A linear asymmetric basin (the Animikie basin) developed as a flexural response to loading of the granite-greenstone terrane.³ Animikie Group sediments (the Thomson Formation) are interpreted as having been deposited dominantly from the north into the northward migrating foreland basin and as having eventually become involved in folding and thrusting during subduction.

Deformation associated with subduction formed the pervasive foliation and lineation of the McGrath Gneiss and isoclinal, recumbent folds with a bedding-subparallel foliation in the Denham and Thomson Formations. Rocks located stratigraphically higher up in the Thomson Formation were deposited late in the deformational history and therefore were not incorporated with subduction. This explains the presence of a tectonic front with highly deformed rocks to the south and less deformed rocks to the north.⁴

A significant problem concerned with the development of orogens involves the observation that a large amount of extension occurs parallel to the belt.⁵ The pervasive east-west, horizontal mineral lineation in the rocks studied here implies a large amount of extension in this direction. Strain analyses by Holst⁶ firmly established the tectonic nature of the bedding-subparallel foliation in the Thomson Formation. His models and various other models (Holm, unpub. M. S. thesis) accounting for a geologically reasonable volume loss and/or rotation of the later deformation all indicate extreme flattening during the early deformation with 2 vertical and large

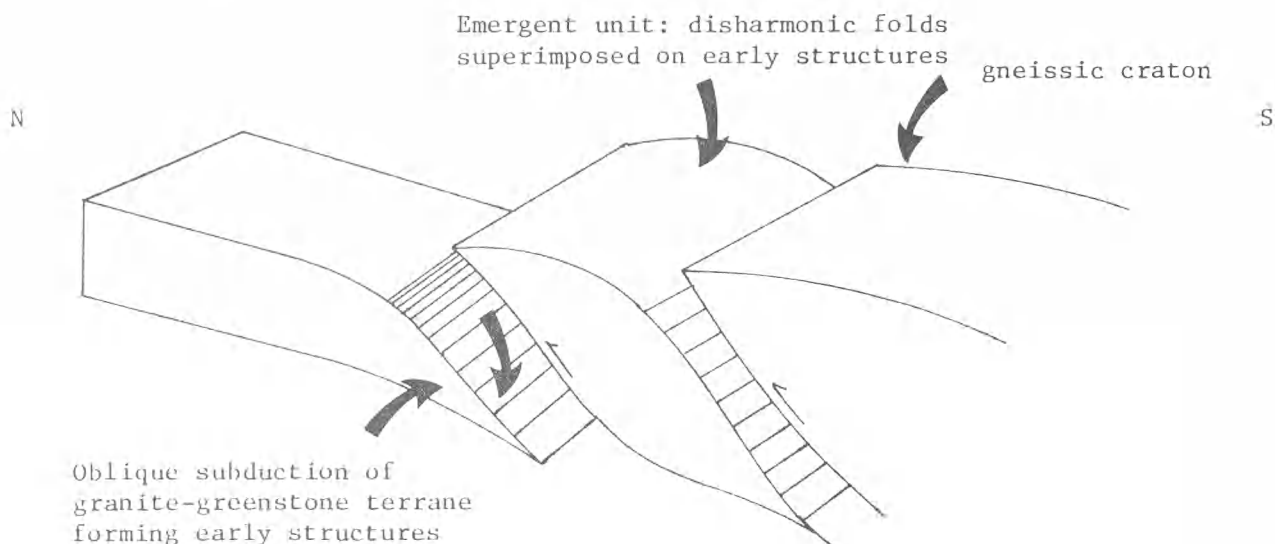
extension in both N-S and E-W directions. The formation of a tectonic fabric involving extension east-west and north-south requires kinematics oblique to the plate boundary, and therefore relative plate motion to be oblique rather than normal as usually interpreted.

Early structures, formed during tectonic burial, were deformed by later more disharmonic structures related to footwall imbrication into the hangingwall during uplift. Continued compression involved basement shortening forming shear zones and high angle reverse faults. Basement involvement during the later deformation formed tight, overturned folds in the overlying Denham Formation and may contribute to the differing structural styles of the Denham and Thomson Formations. Increasing temperature with decreasing pressure is thought to be due to conductive relaxation caused by crustal thickening and erosion.⁷

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References

- ¹Larue, D.K., 1981, Geol. Soc. Am. Bull., Part 1, v. 92, pp. 417-435.
- ²Sims, P.K., and Peterman, Z.E., 1983, Geol. Soc. Am. Memoir 160, pp. 3-14.
- ³Hoffman, P.F., preprint, Proterozoic foredeeps, foredeep magmatism and giant iron-formations.
- ⁴Holst, T.B., 1984, Geol., v. 12, pp. 135-138.
- ⁵Ellis, M.A., Watkinson, A.J., and Ferguson, C.C., in press, Nature.
- ⁶Holst, T.B., 1985, J. Struct. Geol., v. 7, pp. 375-383.
- ⁷England, P.C., and Richardson, S.W., 1977, J. Geol. Soc. Lond., v.134, pp. 201-213.



IRON-FORMATIONS IN THE SUBSURFACE OF SOUTHWESTERN MINNESOTA

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Three core holes were drilled in southwestern Minnesota in the early 1960's by the New Jersey Zinc Company. Drilling probably was targeted on anomalously high magnetic signatures and each hole intersected iron-formation. Two holes were drilled in Traverse County (holes D1 and D4, T. 129 N., R. 47 W., secs. 11 and 10, respectively) and penetrated a total of 950 feet (290 m) of strata of which about 200 feet (61 m) is thinly bedded, magnetite-chert and silicate iron-formation. The iron-formation is interbedded with mafic to felsic volcanic and volcanoclastic rocks, and intruded by diabasic to granitic sills and dikes. The sequence lies with apparent unconformity atop a coarsely crystalline granodioritic gneiss.

More interesting, and possibly more significant is the hole in Lincoln County (hole E1, T. 112 N., R. 46 W., sec. 7). The core consists of about 350 feet (107 m) of thinly bedded to laminated, very fine grained, sedimentary rocks. Major rock types are dark-colored argillite, dark iron-carbonate-rich slate, graphitic slate, green iron-silicate- and chlorite-rich slate, chert, phyllite, and siltstone. All facies of iron-formation deposition are represented within the sequence; however carbonate- and sulfide-rich rocks predominate. The stratigraphic distribution of facies defines an upward-shallowing sequence that passes from predominantly sulfide facies in the basal part to oxide facies and terrigenous deposits in the upper part. The sulfide facies is laminated to thinly bedded, whereas the oxide, silicate and carbonate facies are thicker bedded and have granular textures. Transitions between facies are gradational over short stratigraphic intervals and are characterized by thinly intercalated units. Granules are elliptical concentrations of iron-oxides, iron-carbonate or silicates, 0.5 to 1.5 mm in size, in fine-grained, intergranular matrices of contrasting composition. Several units of iron-carbonate strata contain well developed oolitic textures. Oolites are delineated by concentrically banded iron-oxides filled and surrounded by iron carbonate. Metamorphism to biotite, and locally to garnet zones, is best developed in the thin-bedded silicate- and carbonate-rich units. Porphyroblasts of garnet and magnetite appear to have formed during or after the development of a single, weak, bedding-parallel cleavage.

Although no geochronometric data exist for these rocks, it is possible to speculate about their relative ages from observable compositional, textural and structural attributes. The most significant feature of the Lincoln County sequence is the presence of granular and oolitic textures which are restricted to Early Proterozoic iron-formations. Mineralogic, sedimentological and geochemical similarities also exist between these strata and the Animikie and sub-Animikie rocks exposed in central and northeastern Minnesota, and in the subsurface of northwestern Iowa. In contrast, the Traverse County cores represent a laminated sequence intimately associated with volcanic rocks. Thus, it has attributes typical of many Archean iron-formations, as well as deeper water deposits of Early Proterozoic age.

Geology and Precious Metal Mineralization of the
Silver Creek to Rocking Chair Lakes Area,
Marquette County, Michigan.

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A 5 mi.² (10.4 km.²) area northwest of Marquette, Michigan was geologically mapped at a scale of 1:6,000. The mapped area includes all of sections 10, 15, 23, 24, and 25 and the southern portion of section 14 of T. 49N. R. 28W. The Silver Creek Prospect and many old exploration trenches are located within the area.

The Silver Creek to Rocking Chair Lakes area is dominated by metamorphosed and variably deformed Archean volcanic and intrusive rocks. The oldest rocks are Archean pillowed basalts which have been intruded by Archean gabbro and diabase. These mafic rocks have been intruded by multiple stocks of Archean tonalite. Rhyolite intrusives that cross-cut the basalts and gabbros may have been contemporaneous with the tonalite intrusions. The Archean rocks has been cross-cut by Keweenaw diabase dikes. There are a few small isolated outcrops of Lower Proterozoic slates and quartzites to the south and east of the Archean rocks.

All Archean rock units have been subdivided into highly foliated and (relatively) nonfoliated varieties. In addition, for the basalts a third variety has been added: highly altered basalts. The basalts are generally chlorite hornfels and schistose chlorite basalts. The highly altered basalts are sericite-chlorite-carbonate-quartz hornfels. The gabbros are medium to coarse grained amphibole hornfels. The rhyolite intrusives are dominantly quartz-sericite schists.

The stratigraphic orientation of the basalts is uncertain due to lack of bedding and the high degree of deformation in the area, though pillows give a top direction to the south. Foliations typically strike N 60°W to N 70°W and dip near vertical which is subparallel to the attitude of the rhyolite intrusives. The rhyolite intrusives have probably been intruded along or subparallel to bedding (N 60° to N 70°W). Faults in the area are of two general ages: older, roughly E-W trending faults, which are truncated by younger N-S trending faults. Shear zones are common throughout the area and are most prevalent in the basalts. These shear zones are of both brittle-ductile and ductile types. The sense of displacement is greatest in the vertical sense, but horizontal displacement is evident in deformed pillows.

Anomalous concentrations of gold are associated with pyrite, chalcopyrite, pyrrhotite, and arsenopyrite and occasionally galena and sphalerite in quartz veins. Quartz veins are found in all rock types, are of multiple generations, and are locally abundant. For example, in section 23 there is a quartz vein which is approximately 110 ft. (33 m.) thick. The epigenetic quartz veins are frequently hosted in highly sheared, sericitized, and chloritized basalts and gabbros and highly sheared and sericitized tonalites and rhyolite intrusives. At the Silver Creek Prospect quartz veins containing galena, sphalerite, chalcopyrite, pyrite, and minor arsenopyrite are cross-cut by veins of siderite. The Silver Creek to Rocking Chair Lakes area has structure, alteration, rock types, and numerous quartz veins which are favorable for precious metal mineralization.

Possible Paleocaliche in Portage Lake Volcanics
and the Oronto Group, Northern Michigan

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A complex caliche profile, and numerous widespread zones of carbonate cement occur in a thick sequence of fluvial siliciclastic sandstones and conglomerates that were deposited in the Lake Superior basin during and after continental basaltic volcanism, as interflow conglomerates of the Portage Lake Volcanics and as the Oronto Group. In conglomerates the carbonate cement forms discontinuous zones, up to 60 cm thick and several meters in length, consisting of up to 25 volume % carbonate.

Whereas the caliche horizon at the Centennial Mine shows typical upward-grading features characteristic of pedogenic caliche, the widespread sparry carbonate cement is less diagnostic. It is interpreted also as caliche for the following reasons: 1) it predates regional epidote metamorphism; 2) a caliche profile has been described from the same strata; 3) textures characteristic of caliche such as carbonate-rimmed pebbles, pendulose calcite on pebbles, sand grains floating in a carbonate matrix, and exfoliated chlorite; 4) possible vadoids; 5) the carbonate-rich zones are widespread stratigraphically and geographically in basinward-inclined alluvial fans, and 6) the distribution of these zones, and the total quantity of contained carbonate requires other than a point source for the origin of the carbonate.

Several lines of evidence suggest that the prevailing climate may have been arid, with a fluctuating, perhaps seasonal rainfall pattern required for caliche: 1) a paleolatitude about 30 degrees north; 2) carbonate-filled shrinkage cracks denoting high evaporation; 3) intermittent, flashy, or ephemeral streams recorded locally in fluvial beds by numerous superimposed horizons of mud-chip conglomerate, enormous, previously cemented mudstone rip-ups; and desiccation-cracked mud drapes.

Interpretation of the cement as vadose caliche is compatible with a sedimentation model for the region as a semi-arid intermontane basin, flanked by alluvial fans and with a central saline lake.

Preliminary Magnetic Surveys in Eastern South Dakota,
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Magnetic surveys were conducted in northeastern and east-central South Dakota using total field proton magnetometers on a one mile square grid. The northeastern survey (1000 square miles), near Milbank, crosses the extension of the Morris Fault (the assumed southern boundary of the Great Lakes Tectonic Zone) into South Dakota and an unnamed fault that parallels the Morris Fault 35 miles to the south. The tectonic zone separates a Late Archean (~ 2,700 m.y. old) granite greenstone terrane to the north and an Archean (~ 3,500 m.y. old) granitic gneiss terrane to the south. The unnamed fault separates granitic gneiss rocks to the north and 'undivided' Precambrian rocks to the south.

The magnetic data is characterized by broad wavelength magnetic lows both north of the Morris Fault and south of the unnamed fault. The region in between the faults is characterized by shorter wavelength and greater amplitude magnetic signals with isolated peaks of as much as 2000 gammas greater than those signals outside the region.

The second survey (1500 square miles), near Sioux Falls, is underlain by Sioux Quartzite, granites and granodiorites. A regional magnetic depression is centered at the junction of Minnehaha, Moody and Lake Counties. Previous work in the area on a five mile square mile grid revealed anomalies identified with basic intrusives that were further refined in this study. In addition, this study identified 11 anomalies comparable in amplitude and areal extent to those associated with intrusives and therefore a similar origin is suggested.

Magnetic Studies of Baraboo Interval (Proterozoic) Rocks from Wisconsin.

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The Baraboo Interval rocks as defined by Dott (1983), constitute a series of rhyolites, granites and quartzites dated between 1750 m.y. to 1450 m.y. We report paleomagnetic results for the Baraboo Quartzite of central Wisconsin; the Barron Quartzite of northwestern Wisconsin; and rhyolite and granite inliers of The Fox River Valley.

Baraboo Quartzites: A total of 96 samples from 25 sites associated with the Baraboo Syncline were analyzed (Mercer 1983). Alternating field demagnetization (A.F.), thermal demagnetization and saturation studies indicate that the primary magnetic mineral of the Quartzite is hematite. All samples were routinely thermally demagnetized to 550 C. A fold test (Graham, 1949) on the Quartzite indicates that the magnetism is pre-folding. Attempts at making structural corrections for the rhyolites resulted in a negative fold test.

Barron Quartzite: The Barron Quartzite is interpreted to be a broad north northwesterly, gently plunging syncline. A total of 41 hand samples were collected from six sites of quartzite. Another five samples were taken from the overlying Cambrian age breccia (Wolski, 1985).

Thermal demagnetization studies show the magnetism is carried by hematite. Samples were routinely demagnetized to 600 C. A fold test proved to be positive for the Barron Quartzite. A conglomerate test performed on Barron Quartzite clasts from the overlying breccia indicates that the magnetism is at least Precambrian.

Fox River Valley Inliers: Forty four samples from six rhyolite and granite inliers and two associated dikes in the Fox River Valley area of south-central Wisconsin were analyzed to determine their magnetic characteristics. Interpretation of magnetic mineralogy was based on A. F. and thermal demagnetization curves. Remanence is carried by spinel minerals (magnetite and maghemite) and all sites have at least two components of magnetization (Henckel, 1985).

The results from these samples are more difficult to interpret because of the strong remagnetization which probably occurred at 1630 m.y. The best fit paleopoles for all the formations is given in table 1 and figure 1.

Conclusions: When these pole positions are considered in reference to established polar wander curves (Irving, 1979) we conclude that: A) The Barron Quartzite is younger than the Baraboo Quartzite. B) The magnetism of Fox River Valley inliers is probably that of 1630 m.y. C) The offset of the Baraboo Interval polar wander curve, from the reference curve, may indicate tectonic movement of the area during Proterozoic time.

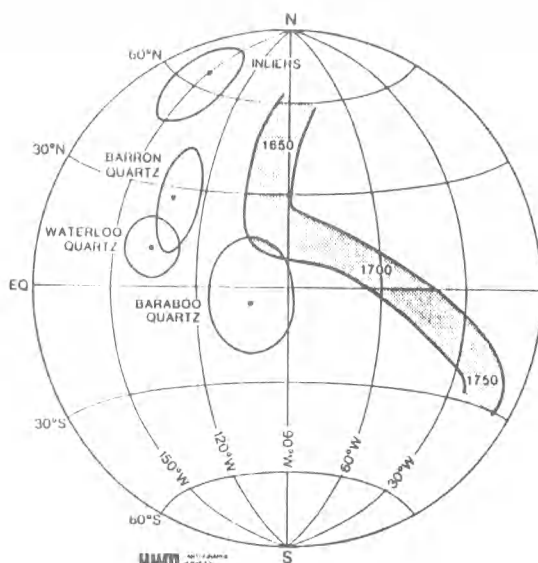
References

- 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, pp. 129-141.
- Graham, J.W., 1949, The stability and significance of magnetism in sedimentary rocks: J. Geophys. Res., p. 131-161.
- Henckel, E., 1985, Paleomagnetic study of rhyolites and granites in the Fox River Valley area of south-central Wisconsin. M.S. Thesis, UW-Milwaukee.
- Irving, E., 1979, Paleopoles and paleolatitudes of North America and speculations about displaced terrains. C.J. Earth. Sci., vol. 16, pp. 669-694.
- Mercer, D., 1984, Paleomagnetism of the Baraboo Quartzite M.S. Thesis, UW-Milwaukee.
- Wolske, R., 1985, Paleomagnetic study of the Barron Quartzite of Northwestern Wisconsin, M.S. Thesis, UW-Milwaukee.

Table 1. Paleopole Positions for Baraboo Interval Rocks

FORMATION	VGP	δp	δm	Number of sites	Number of specimens
Granitic and Rhyolitic Inliers	N 67.5W 149.8	21.23	27.63	6	44
Baraboo Quartzite	S 5, W 104	17.2	19.2	6	31
Waterloo Quartzite	N 14, W 139	10.0	10.6	1	18
Barron Quartzite	N 27, W 135	14.5	21.4	6	41

Figure 1. Pole positions for Baraboo Interval Rocks. Polarwander path modified from Irving 1979.



TRANPOSED PLANAR AND LINEAR FABRICS IN
ROCKS OF THE HERON BAY - HEMLO SUPRACRUSTAL
SEQUENCE

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Detailed mapping of mesoscopic structures has been initiated in rocks east of the Coldwell Complex in an Archean metavolcanic and metasedimentary terrane. This area forms part of the Wawa subprovince of the Superior Structural Province.

Although the data are sketchy at this time, some observations and interpretations appear warranted.

Redeformed folds have been documented in several locations, particularly in the vicinity of Heron Bay. Dominant fold hinge lines (F_2) plunge steeply to the west paralleling the dominant linear fabric of the rocks. The folds possess an axial planar schistosity which represents the dominant planar fabric element regionally. Eastward, a mesoscopic down-facing antiformal structure has been mapped in the vicinity of the Hemlo deposit. The plunge of the fold hinge as well as the regional plunge of the linear fabric is eastward. The change from westward to eastward plunge may reflect a curvilinear regional pattern of fold hinges and linear fabric elements in general.

A variety of "clastic" rocks have been reported in the area. Examination of several occurrences appears to suggest that in at least some cases these clastic rocks are the result of tectonism and represent fragmented rocks produced by deformation of initially layered sequences.

Primary stratigraphic relationships for many lithologies cannot be established with any degree of certainty. Evidence for extensive transposition exists, suggesting that the succession of rocks in the region reflect a variety of structures, metamorphic histories, and initial depositional environments which are now juxtaposed along zones of shear discontinuity.

GEOLOGY AND METALLOGENY OF PROTEROZOIC BASEMENT TERRANES IN MISSOURI

by

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The Precambrian basement in Missouri comprises two distinct tectonostratigraphic terranes: an Early Proterozoic orogenic terrane composed of a great variety of metasedimentary and metaigneous rocks, and a Middle Proterozoic anorogenic terrane of unmetamorphosed epizonal granite and rhyolite. The metamorphic rocks, buried below the cover of platform-type Paleozoic strata, are part of the Central Plains orogen (1.6 to 1.8 Ga) which extends from Kansas and Nebraska into Missouri. They are known only from drill holes and underlie western, northwestern, and central Missouri. The terrane projects a dominant northwesterly structural grain reflected in the overlying Paleozoic strata by tectonic zones and strikingly expressed on aeromagnetic maps by linear anomalies of regional extent. On the northeast, the terrane is bounded by the Missouri gravity low, a continental-scale geophysical anomaly; on the southwest, it is apparently bounded by the Chesapeake tectonic zone; and on the south, it is overlapped and truncated by the Middle Proterozoic terrane.

The Central Plains orogen comprises several parallel, northwest-striking foldbelts and bears the hallmark of a major Early Proterozoic plate collision. Available data suggest that metamorphic grade increases from lower greenschist to amphibolite facies in a northeasterly direction, perpendicular to the strike of the foldbelts. This is best documented across the Central Missouri structural high where the increasing metamorphic grade may be the function of deeper erosional levels in the uplifted basement complex. Locally, the terrane is intruded by layered mafic complexes and undeformed mesozonal granite plutons. The latter are coeval with the anorogenic magmatism that formed the epizonal rocks of the Middle Proterozoic.

The anorogenic granite-rhyolite terrane is partly exposed in the St. Francois Mountains in southeastern Missouri. Several hundred drill holes indicate that it underlies most of the southern half of the state and extends into Oklahoma, Arkansas, and Illinois. It is characterized by the predominance of silicic over mafic rocks, the sparsity of intermediate rocks, and a potassium-dominant, moderately alkali-rich chemistry. The formation of this terrane involved large-scale melting of the lower crust in a tensional tectonic regime and contributed to the cratonization of the continent. Detailed studies in southeastern Missouri, where outcrop, drill hole, and aeromagnetic data can be fortuitously integrated, suggest that the emplacement of silicic magmas in the upper crust during the Middle Proterozoic resulted in widespread eruption of large volumes of ash flows, cauldron subsidence, ring complex formation, and intrusion of central plutons in some resurgent cauldrons.

The bulk of the epizonal rocks in southeastern Missouri was emplaced 1.45 to 1.48 Ga ago (St. Francois terrane); similar rocks in southwestern Missouri and adjoining states are approximately 100 million years younger (Spavinaw terrane). Both 1.35 and 1.45 Ga old granite plutons intrude the Central Plains orogen; this suggests that the Middle Proterozoic epizonal terranes and associated volcanic rocks were more extensive and covered a much larger part of

the orogenic belt before uplift and attendant erosion removed them. The undeformed mesozonal plutons, invading, perforating, and partly assimilating the older terrane, may therefore represent the roots of the anorogenic terranes.

Ore deposits are not known in the buried Early Proterozoic terrane, but the lithologies and style of deformation associated with it suggest that its metallogeny is analogous to that of Proterozoic orogenic belts in the Canadian Shield. A diverse group of ore deposits may be envisaged in the collision-subduction regime of the foldbelts, including volcanogenic massive sulfides and hydrothermal veins of the base metals and gold. Cratonization of the continent, rifting, and basin formation may have given rise to Superior-type iron formations and gold-bearing, uranium-rich conglomerates. Continental-margin rifting allowed the emplacement of mafic complexes which may contain Fe-Ni-Cu-Cr-Pt deposits that rival those of the other shields.

The St. Francois terrane contains iron, manganese, and Pb-Ag-W-Sn deposits. Its metallogeny is a function of the tectono-magmatic processes that produced it. The emplacement of the ore bodies is controlled by ring fractures and associated intrusions. The iron ores are Kiruna-type (non-titaniferous, apatite-bearing) magnetite and hematite with relatively high alkali and rare-earths contents. They have been a continuous source of production since 1815. They are associated with trachyte-syenite ring intrusions and are emplaced as magmatic injections and hydrothermal veins in rhyolite. They may have been derived through remobilization of postulated iron formations of the Early Proterozoic terrane. The Pb-Ag-W-Sn deposits in the Silver Mine district are the only known high-temperature xenothermal veins in the Proterozoic of the entire mid-continent. They are associated with the Silvermine ring intrusion, and it is tempting to speculate that there are similar deposits in the buried parts of the terrane. The widespread occurrence of uraniferous tin granites suggests that the St. Francois terrane is a tin metallogenic province with potential concentrations of U-Th-Sn and rare earths.

The huge unexplored region of the buried Proterozoic terranes in the mid-continent is one of the last frontiers for geologic exploration. It potentially contains some of the largest and richest undiscovered ore deposits of North America.

Precambrian Basement of the Dakotas and its Relationship to
Exposed Precambrian Terrane

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The Precambrian basement rocks of North and South Dakota may be divided into several distinct lithotectonic terranes on the basis of drill hole, gravity and magnetic data. Archean gneiss and granite-greenstone terranes underlie eastern North Dakota and northeastern South Dakota. Early Proterozoic gneiss and metasedimentary rocks underlie most of the western third of the Dakotas, except for the Black Hills region of South Dakota where there are exposed Archean rocks. Between the Proterozoic rocks to the west and the Archean rocks to the east is a broad transition zone of strongly overprinted Archean crust. A large Early Proterozoic batholith underlies south-central South Dakota, with Early Proterozoic felsic volcanic rocks to the east and a diverse assemblage of basement rocks, including some of Archean age, in the extreme southeastern portion of the state.

Major tectonic and lithologic units of the Precambrian provinces of the adjoining regions to the north, east, and west can be projected into the Dakotas on the basis of their characteristic geophysical signatures and in conjunction with drill-hole data. Churchill Province rocks of the Trans-Hudson foldbelt, which borders the Superior craton of the Canadian Shield, project southward into the western Dakotas. The Thompson nickel belt and Pickwitonei gneiss belt correlate with the western and eastern halves, respectively, of the transition zone between the Archean and the Proterozoic crust. On the west the Wyoming craton extends to the Black Hills region and the Cheyenne foldbelt projects into southwest South Dakota. Although Archean rocks extend into the eastern Dakotas from Minnesota, the Penokeyan foldbelt of Michigan and Wisconsin cannot be traced into the Dakotas but may extend into northwest Iowa.

Tectonic evolution of the Early Proterozoic terrane in the Dakotas most probably follows collisional plate tectonic models proposed for the evolution of the Trans-Hudson foldbelt in the Churchill Province in Canada. As in the Churchill Province, Early Proterozoic rocks underlie the western Dakotas, but it is not known whether these Early Proterozoic rocks formed through rifting and subsequent closure of a once extensive Archean crust or through collision of previously widely separated Archean crustal blocks.

THE PETROLOGY AND GEOCHEMISTRY OF THE POTATO RIVER INTRUSION
(EASTERN MELLEEN COMPLEX), NORTHERN WISCONSIN

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ABSTRACT

The Mellen complex of northern Wisconsin is a plutonic complex emplaced near the base of the Keweenaw volcanic sequence. It is composed of gabbroic western (the Mineral Lake and Rearing Pond intrusions, Olmsted, 1969; 1979) and eastern halves separated by a granitic stock (the Mellen granite). The Mellen complex has been dated by several authors using a variety of methods. The Mineral Lake intrusion is about 1049 Ma (Seifert et al., 1985) while the Mellen granite is about 1000 Ma (Silver and Green, 1972).

The eastern half of the complex has been studied by Tabet and Mangham (1978) who called it the eastern Mellen intrusive complex. In order to avoid confusion with the complex as a whole, I propose the name Potato River intrusion for the eastern half, after the exposures along the Potato River. It must be noted, however, that the eastern and western halves are probably correlative in part and are thus not strictly separate bodies.

The Potato River intrusion (PRI) is a gabbroic pluton emplaced semi-concordantly along what was probably an unconformity in the Keweenaw Powder Mill group volcanics. The margins of the intrusion are in contact with the volcanics, except the southwestern and western margins. The intrusion strikes about N70E and dips about 60NW. The PRI was most likely emplaced as a flattened-funnel shaped magma chamber similar to that proposed by Irvine and Smith (1967) for the Muskox intrusion. Subsequent tilting and faulting has exposed the body at slightly varying levels.

The Potato River intrusion has been divided into several zones based upon rock type. Lowermost is a border zone which is an irregular zone of chilled-margin rock cut by later diabasic dikes (chilled-margin composition: $\text{SiO}_2=46.42\%$, $\text{TiO}_2=1.92\%$, $\text{Al}_2\text{O}_3=13.79\%$, $\text{Fe}_2\text{O}_3=2.18\%$, $\text{FeO}=13.83\%$, $\text{MnO}=0.21\%$, $\text{MgO}=8.51\%$, $\text{CaO}=9.26\%$, $\text{Na}_2\text{O}=2.15\%$, $\text{K}_2\text{O}=0.50\%$, $\text{P}_2\text{O}_5=0.23\%$). The bulk of the intrusion is the main zone composed of fine- to medium-grained cryptically layered gabbroic rocks ranging from olivine gabbro through leucogabbro and quartz gabbro to ferrodiorite. This main zone has been divided into upper and lower parts by a picritic zone consisting of a lower several-meter-thick layer of picrite and an upper horizon of troctolite and layered troctolite which locally exhibits rhythmic modal layering. Lastly, an upper zone consists of "granophyric" and granitic rocks.

The main zone of the intrusion probably formed from a single magma. After about one third of the magma had crystallized, the picritic magma was emplaced into the chamber along the interface between the

accumulated crystals and the overlying magma. The picrite itself is composed of two distinct size populations of olivine (2mm and .25mm) along with either platy or interstitial plagioclase and poikilitic clinopyroxene. The origin of this magma and its relation to the PRI are enigmatic. Two distinct, and opposite, possibilities are likely. From modelling of the major elements it appears that the picrite could be a primitive magma parental to the chilled-margin (after fractionation of 38% olivine, Fo61 and 1% plagioclase, An70) or it could be derived by accumulation of olivine and plagioclase (in the above proportions) in a magma of the chilled-margin composition. A major problem with the first explanation is that the picrite is very iron-rich (Mg# = 56) and thus is not similar to other ultramafic magmas. The major problem with the second explanation is that the plagioclase crystals of the picrite and the overlying troctolites have a high aspect ratio suggesting greater undercooling (i.e., a magma with a higher liquidus temperature) than the rest of the intrusion. A third possibility is that the picrite and the chilled-margin magmas are not directly related.

Towards the very end of crystallization of the PRI the last remaining residual liquids were contaminated by partial melts of the crust, yielding some of the upper zone rocks. This contamination/mixing hypothesis is supported by the trends of some granitic rocks on incompatible-trace-element variation diagrams, where the granitic rocks diverge from the main evolutionary trend of the other rocks. These granites can not be derived by fractional crystallization of the gabbroic series because: trace element compositions are inconsistent, the "granophyres" are volumetrically too abundant, and there is field and thin section evidence for magma mixing and intrusive relationships.

REFERENCES

- Irvine, T.N., and C.H. Smith, 1967, The ultramafic rocks of the Muskox intrusion, Northwest Territories, Canada, in Wyllie, P.J., ed., *Ultramafic and Related Rocks*, John Wiley and Sons, New York, 38-49.
- Olmsted, J.F., 1969, Petrology of the Mineral Lake intrusion, northwestern Wisconsin, in Isachsen, Y.W., ed., *Origin of Anorthosite and Related Rocks*, New York State Museum and Science Service Memoir 18:149-161.
- , 1979, Crystallization history and textures of the Rearing Pond gabbro, northwestern Wisconsin, *Amer. Mineral.* 64:844-855.
- Seifert, K.E., Z.E. Peterman and K.E. Windom, 1985, Mineral Lake layered intrusion, NW Wisconsin, *Geol. Soc. Amer. Abstr. with Programs* 17:712.
- Silver, L.T. and J.C. Green, 1972, Time constraints for Keweenaw igneous activity, *Geol. Soc. Amer. Abstr. with Programs* 4:665-666.
- Tabet, D.E. and J.R. Mangham, 1978, The geology of the eastern Mellen intrusive complex, Wisconsin, *Geoscience Wisconsin* 3:1-19.

CARBON ISOTOPE SYSTEMATICS IN THE LAKE SUPERIOR REGION
FROM 1.6 TO 2.5 Ga

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The fractionation of carbon isotopes results in the creation of two major compartments in the sedimentary record: carbonate carbon and organic carbon. $\delta^{13}\text{C}$ ratios of the carbonate fraction average around 0 ‰ (PDB) while those of organic carbon average around -25 ‰. Post depositional alteration may cause shifts in these values that must be determined for accurate interpretation of carbon isotope analyses.

A number of studies have been done in recent years on the carbon isotope composition of carbonate and organic carbon bearing rocks of Precambrian age. Data have been collected from relatively few localities, with the bulk of the work being concentrated in south Africa. Information on the carbon isotope composition of the Canadian shield is limited.

Three suites of samples were collected from three distinct depositional basins in the Lake Superior region. Eight samples were collected from the Marquette district, including the Kona dolomite, Wewe slate, Siamo slate, and the Michigamme slate. Three samples were collected from the Iron River - Crystal Falls district including stromatolitic dolomite from the Randville dolomite, black slate from the Michigamme Formation, and the Marquette anthracite (Tyler et al., 1957). Two samples were collected from the Gogebic district. These consisted of siderite iron formation and arkosic quartzite from the Tyler Formation. Anthraxolite from the Gunflint chert in Ontario and a black shale from the Baraboo interval sediments at Powers Bluff in Wisconsin were also analyzed. The ages of the rocks sampled range from 1.6 to 2.5 Ga.

Carbon isotope composition of these samples are being analyzed in order to make inferences about the Precambrian atmosphere and biosphere. Comparisons will be made within each district sampled as well as across district boundaries. The effects of post diagenetic fractionation will be examined and compensated for where metamorphic grade is well constrained.

This work will serve to increase the database on carbon isotope composition of Precambrian rocks, particularly in the Lake Superior region, and aid in the overall understanding of the evolution of Earth's early atmosphere and biosphere.

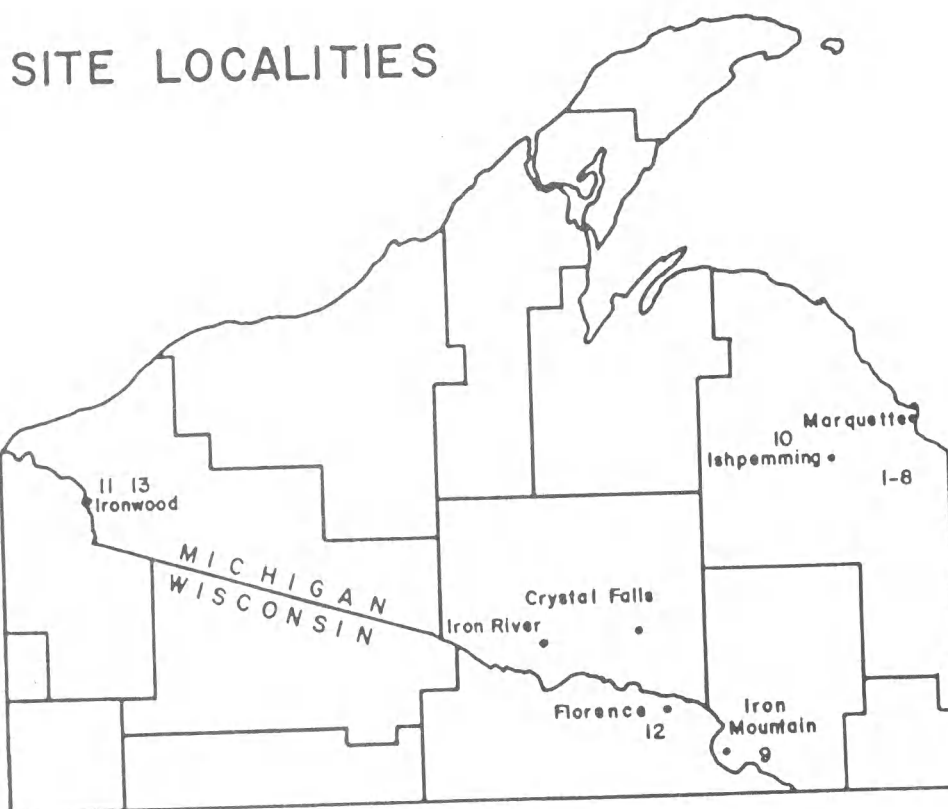
Gene LaBerge is thanked for providing samples of the Marquette Anthracite and Gunflint Anthraxolite.

REFERENCES

- KING, PHILIP B. (1976) Precambrian Geology in the United States: An Explanatory Text to Accompany the Geologic Map of the United States, Geological Survey Professional Paper 902, United States Government Printing Office : Washington.

OEHLER, D., SCHOPF, J.W., AND KVENVOLDEN, K.A. (1972) Carbon Isotopic studies of Organic Matter in Precambrian Rocks, Science 175:1246-1248.

TYLER, S.A., BARGHOORN, E.S., AND BARRETT, L.P., (1957) Anthracitic Coal from Precambrian Upper Huronian Black Shale of the Iron River District, Northern Michigan, Bulletin of the Geological Society of America 68 : 1293-1304.



MINERAL POTENTIAL EVALUATION OF AN IRON-RICH VOLCANOGENIC METASEDIMENT,
GLEN TOWNSHIP, EAST-CENTRAL MINNESOTA

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Abstract

A number of economic gold deposits result from deformation and hydrothermal enrichment of volcanogenic iron-rich sediments. In east-central Minnesota the Glen Township Formation has many of the lithologic and metamorphic characteristics of rocks hosting this type of deposit. Airborne magnetic and electromagnetic surveys correlate with geology to map the near surface areal distribution of the formation. Drill core samples have gold contents consistent with a protore for this type deposit with some higher assays, to 1.41 ppm, indicating remobilization and hydrothermal concentration.

The DNR completed studies of the formation to: 1) define deforming structures and measure the magnitude of deformation, 2) to examine deformed zones for alteration and mineralization, 3) to evaluate geophysical methods capable of defining near surface and deep mineral potential targets likely to be found in Minnesota. Magnetometer and HLEM Surveys map the formation where it is near surface. VLF-EM surveys and refraction seismic profiles define a strong east-west fault zone. A Controlled Source Audio Frequency Magnetotelluric Survey (CSAMT) mapped the formation to a depth of 1400 meters and displayed a 1000 meter vertical displacement across the fault. Core drilling intersected the top of the Glen Township Formation on the downthrown side of the fault, at 625 feet and an extensive fault zone at 1200 feet down the hole, as indicated by the CSAMT survey. The core displays alteration, minerals and anomalous gold values from hydrothermal solution movement in the fault zone.

The Douglas Fault at Amnicon Falls State Park, Wisconsin:
Brittle Cataclastic Textures in Keweenawan rocks

by G. A. Ludvigson and R. A. Anderson, Iowa Geological Survey

The Douglas Fault, a southeasterly-dipping reverse fault, forms the northwest boundary of the St. Croix horst in northwest Wisconsin and east-central Minnesota. Exposures of the Douglas Fault at Amnicon Falls State Park in Douglas County, Wisconsin, where the structure is transected by the northwesterly-flowing Amnicon River, provide a glimpse at the suite of deformational features associated with the structure. A reconnaissance field study at Amnicon Falls was initiated to examine the styles of deformation on several scales, to determine the approximate width of rock deformation exposed, and to make a preliminary assessment of the potential for using petrographic studies to interpret cross-cutting sequences of microstructures which record ancient movements along the Douglas Fault.

The falls plunge over a reverse-faulted contact between Keweenawan basalts (upstream) and flat-lying Keweenawan sandstones, reportedly of the Bayfield Group (Craddock et al. 1983, p. 91). Two obvious features at this contact zone (CZ) are a 2-3 m thick body of friable breccia consisting of mm to dm-sized clasts of basalt and sandstone separating the hanging and foot walls, and a narrow belt of steeply dipping conglomeratic sandstones extending approximately 10m to the northwest of the CZ. The friable breccia is poorly exposed at the base of the falls, and dips beneath the basalts of the hanging wall. Immediately upstream from the CZ, a variety of brittle microstructures are exposed in the basalts of the hanging wall. These include: 1) Mesofaults with various orientations, with slickensides developed on opposing surfaces. Many of these surfaces have "rough facets" (Angelier et al. 1985, p. 352) which were protected from tooling by the opposing wall. These protected areas are coated by calcite cement. 2) Swarms of anastomosing zeolite and calcite veinlets (0.1 to 3 mm wide) cutting basalts. Complex cross-cutting relationships between different veinlets and microfaults indicates that these brittle microstructures record multiple deformations. 3) Gouge (10-30 μ diam.) dominated microbreccias (max. clast diameter 1 cm) consisting of fragments of basalt and early-formed zeolite and calcite veinlets. The prevalence of "stable fracturing" (Mitra, 1984, p. 53) within these rocks indicates that cataclastic flow occurred during their development, and suggests that large displacements may be present within the rocks exposed upstream from the CZ. A reconnaissance traverse reveals that discreet 1-10 m-wide "brittle deformation zones" (Mitra, 1984, p. 53) paralleling the CZ can be easily recognized on the outcrop scale, extending at least 400 m upstream from the CZ. These observations indicate that the Douglas Fault is a wide zone of inhomogeneous brittle deformation, perhaps wider than previously suspected.

Petrographic examination of zeolite and calcite veinlets reveals that most contain inclusion trains that perfectly mimic the margins of the vein wall. These are interpreted to be compound "crack-seal" veins formed by the pressure-solution processes described by Ramsey (1980). The distribution, orientations, and spacing of glide twins in larger calcite veinlets (5 mm wide) shows that the interiors of these veins are more highly strained than the outer zones, confirming that these features grew inward-out as a consequence of successive, incremental strains. Many late-formed veinlets have original s-shaped margins with tapered ends, and are interpreted to be pull-apart voids which developed along curving shear fractures. A preliminary evaluation of zeolite mineral stoichiometry by ED spectra from electron probe microanalyses indicates that potassium-rich (phillipsite?) and sodium-rich (natrolite?) varieties are present.

Modal analyses of samples from the steeply-dipping sandstone of the CZ (Q₆₉F₁₀L₂₁) and the flat-lying sandstones immediately to the northwest (Q₅₅F₂₇L₁₈) reveal compositional similarities to the Fond du Lac Fm. as described by Morey and Ojakangas (1982). Microstructures indicating brittle or ductile modes of deformation in the sandstones were not found in the two thin sections examined for this study. These observations suggest that: 1) major movements along the Douglas Fault preceded the lithification of the Bayfield Group, as suggested earlier by Craddock (1972, p. 423), and 2) the steeply-dipping sandstones at the CZ apparently have not suffered ductile deformation, and possibly are contained within a narrow rotated fault block, rather than having been drag-folded into their present orientation.

References Cited:

- Angelier, A., Colletta, B., and Anderson, R. E., 1985, *Geol. Soc. of America Bull.*, v. 96, p. 347-361.
- Craddock, C., 1972, in Sims, P. K., and Morey, G. B., eds., *Geology of Minnesota: a centennial volume*: St. Paul, Minnesota Geol. Survey, p. 416-424.
- Craddock, C., Mudrey, M. G., and Holst, T. B., 1983, in Shaver, R. H., and Sunderman, J. A., eds., *Field Trips in Midwestern Geology (Ann. Mtg. GSA)*: Bloomington, Indiana Geol. Survey, p. 77-104.
- Mitra, G., 1984, *Jour. Structural Geol.*, v. 6, p. 51-61.
- Morey, G. B., and Ojakangas, R. W., 1982, *Geol. Soc. America, Memoir 156*, p. 135-146.
- Ramsey, J. G., 1980, *Nature*, v. 284, p. 135-139.

Penokean metamorphism in the Black River Valley, central Wisconsin:
Greenschist to amphibolite facies transition

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Data from the Black River Valley suggest that metamorphism during the Penokean orogeny was predominantly amphibolite facies, but that it locally varies continuously from greenschist facies to amphibolite facies.

Rocks exposed along the Black River include banded gneisses that are approximately 2800 and 2500 m.y.-old, a 2530 m.y.-old syenitic pluton, and 1870-1830 m.y.-old intrusive rocks emplaced during the Penokean orogeny. All of these rocks have been deformed and metamorphosed during the Penokean orogeny. Penokean amphibolite-facies metamorphism has affected late-kinematic Penokean mafic dikes at Black River Falls and Neillsville and 1832±9 m.y.-old foliated tonalite at Greenwood. Electron microprobe analysis of coexisting plagioclase and amphibole in selected samples of mafic rock, combined with petrographic examination of other samples, indicates that most of the rocks between Black River Falls on the south and Greenwood on the north (55 km distance) are metamorphosed to amphibolite facies. However, a gradual transition from lower(?) greenschist facies to amphibolite facies is recorded by mineral assemblages and recrystallization textures along a south-to-north traverse of approximately 12 km between Halls Creek and the northern end of Lake Arbutus, in the vicinity of Hatfield. The traverse is nearly perpendicular to WNW-striking lithologic layering and layer-parallel foliation.

Iron-rich pelitic schist at Halls Creek with well-preserved hematite oolites, which is tentatively interpreted to be metamorphosed to the chlorite zone, contains the assemblage muscovite + chlorite + quartz + hematite. The greenschist facies mineral pair actinolite + albite is present in relatively poorly recrystallized greenschist located 1 km to the north. The same mineral pair also occurs in slightly better recrystallized greenschist 0.6 km farther north. Other minerals in these two greenschists are chlorite, epidote, carbonate and opaque minerals. A considerably better recrystallized mafic rock located an additional 2.3 km to the north, near a powerhouse, contains the mineral pair hornblende + albite, indicative of metamorphism to the transition zone between greenschist and amphibolite facies. Plagioclase in this rock contains a few cores of andesine that are interpreted to be relict igneous compositions. Transition zone metamorphism of banded gneiss at a dam at the southern end of Lake Arbutus, 4.5 km north of the powerhouse, is signified by coexistence of hornblende + albite + oligoclase in a mafic layer. The amphibolite facies pair hornblende + oligoclase-andesine is present in a mafic layer of gneiss at Big Spring along the NW shore of Lake Arbutus, 4 km north of the dam. Contact metamorphism by nearby late-Penokean granite (mildly deformed) has produced actinolitic hornblende, albite, chlorite, epidote, and sericite in gneiss at Big Spring. Low-grade static metamorphism of unknown age is recorded in basalt dikes and gabbro near the dam.

The results support the conclusion of Maass and others (1985) that metamorphism during the Penokean orogeny spans the full range from greenschist to amphibolite facies.

Maass, R. S., Brown, B. A., and Greenberg, J. K., 1985, Two early Proterozoic successions in central Wisconsin and their tectonic significance: Alternative Interpretation: Geological Society of America Bulletin, v. 96, p. 1340-1344.

TECTONIC EVOLUTION OF THE FELCH TROUGH

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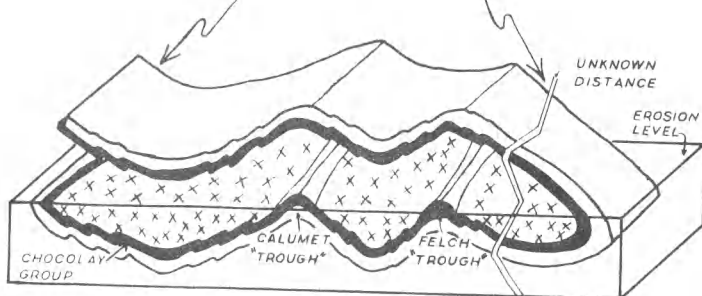
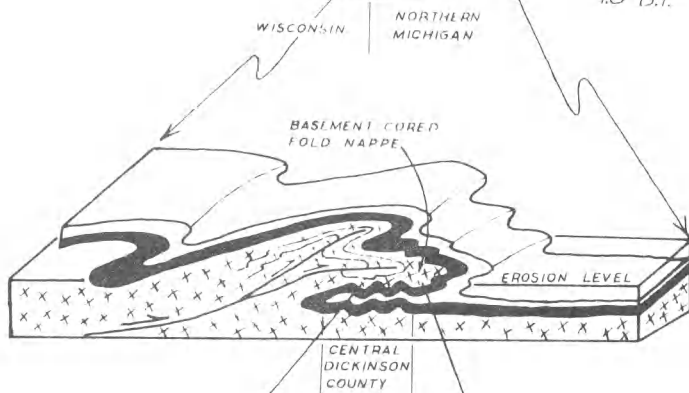
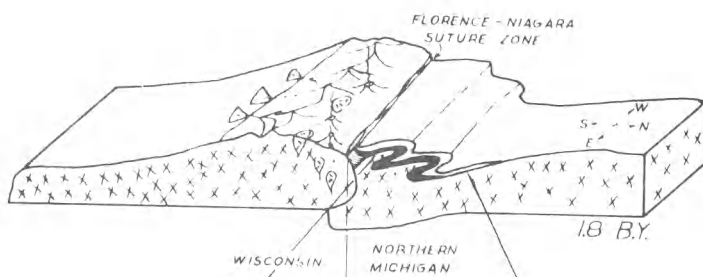
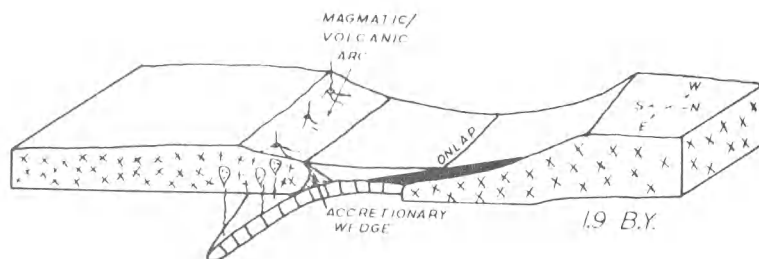
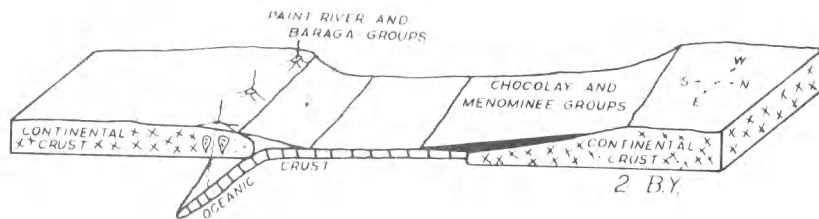
A new structural interpretation is proposed for the Felch "trough" of central Dickinson County, MI based on a detailed structural investigation of the region. Traditional views (e.g., James et al., 1961) are that the Lower Proterozoic metasedimentary rocks of the Chocoday and Menominee Groups are faulted and folded into a west-plunging, asymmetric syncline overturned to the south. New data from the present study, including stratigraphic younging directions and minor fold relations, along with recent work by Mancuso et al. (1984), indicate that the Felch "trough" is an antiform developed in an overturned stratigraphic sequence (Fig. 1).

Two phases of mesoscopic folding are recorded in the Chocoday Group metasediments. S1 generally dips SE and varies from a schistosity in micaceous rocks to a spaced cleavage in quartz-rich rocks. S1 is axial planar to nearly recumbent F1 isoclinal folds. Bedding-cleavage relations show that F1 folds belong to a nearly horizontal, north-directed, recumbent fold system. S2 is a NW-dipping crenulation cleavage that is axial planar to upright F2 folds. F2 folds are coaxial with F1 structures.

Bedding-cleavage relations and minor fold asymmetry suggest that the Felch "trough" is an F2 structure developed on the overturned limb of a regional F1 recumbent fold. The "trough" may consist of a single F2 antiform or may be on the south limb of a larger F2 antiform whose axis lies to the north. The magnitude of the F1 recumbent fold is unknown, but reinterpretation of data from other areas in central Dickinson County suggests that overturned strata may be common; hence, the F1 fold exposed in the Felch "trough" may be regional in extent. Based on this interpretation, the following model for the tectonic evolution of the region is proposed (Fig. 1): 1. Early Proterozoic continental collision associated with the Penokean orogeny juxtaposed the Baraga, Chocoday, and Menominee Groups and formed the Florence-Niagara suture zone (Ueng and Larue, 1984). 2. Deformation associated with this collision produced a basement-cored fold nappe that was transported to the north (F1). 3. A younger phase of folding (F2) deformed this nappe and produced, after erosion, the Felch "trough" along with the other belts of metasedimentary rocks in central Dickinson County.

REFERENCES

- James, H.L., Clark, L.D., Lamey, C.D., and Pettijohn, F.J., 1961, The geology of central Dickinson County, Michigan: U.S. Geol. Survey Prof. Paper 310, 176 p.
- Mancuso, J.J., Brown, R., Harrison, J., Maharidge, A.D., Pennington, R., and Walden, R., 1984, The geology of the Groveland Mine, Felch District, Michigan: 13th Ann. Inst. on the Lake Superior Geol., Abstr., p. 30.
- Ueng, W.L., Larue, D.K., and Sedlock, R.L., 1984, Geologic history and palinspastic reconstruction of the Early Proterozoic Penokean collision zone: 13th Ann. Inst. on the Lake Superior Geol., Abstr., p. 78.



CHROMIUM-RICH BASAL PILLOW LAVAS OF THE KEWEENAWAN SIEMENS
CREEK FORMATION, NORTHERN MICHIGAN

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Basal pillow lavas of the Siemens Creek Formation of the Powder Mill Group are exposed intermittently along the contact with the underlying Bessemer Quartzite. These low-Al porphyritic lavas, with up to 40 volume % phenocrysts, have higher Cr concentrations (~950-1150 ppm) and MgO (12-13.7%) than the younger tholeiitic lavas of the Powder Mill Group (<450 ppm Cr and 8.8% MgO), and to the diabase dike swarms of comparable age (Burgess et. al., and Gell, this conference). In the Bond Falls Storage Basin area a lake side exposure of oblate pillows (0.2 to 0.4 m long) contain phenocrysts of serpentinized pseudomorphs of olivine(?), primary chromite, and Cr-rich (Cr₂O₃ up to 1.12%) pyroxene in a matrix of pyroxene, plagioclase, magnetite, and ilmenite.

The altered olivine occurs as sub- to euhedral grains ~1 to 8 mm in size. The sub- to euhedral chromite grains are ~0.06 mm, mostly within the altered olivine or, less commonly, within the pyroxene phenocrysts. Three pyroxene morphologies are evident: 1) Matrix pyroxenes, mostly <0.5 mm. 2) Sub- to euhedral phenocrysts from ~2 to 4 mm, some of which are sector zoned. 3) "Clots" of pyroxene, 3 to 6 mm, with finer-grained anhedral grains in the interiors and coarser subhedral grains at the margins. Exsolution zones of subcalcic pyroxene are up to 40-50 microns wide in some phenocrysts.

The plagioclase grains, AN₄₀₋₇₀, decrease in FeO(T) from 0.91 to 0.51 and K₂O from 0.77 to 0.18 with increasing AN number. The chromite have cation proportions based on 32 oxygens as follows: Mg²⁺ 1.70-3.46; Cr³⁺ 8.21-10.15; Al³⁺ 4.05-4.98; Ti⁴⁺ 0.20-0.65. The trivalent cation ratio (Cr/Cr+Al) and Mg number (Mg/Mg+Fe²⁺) correlate highly (r²=0.9706). The composition of the pyroxene "clots" and phenocrysts is essentially similar and can be characterized as Wo₃₇En₅₁Fs₁₂. Matrix pyroxenes range from this composition to Fe enriched Wo₃₈En₅₂Fs₃₂. The composition of the subcalcic exsolution matrix pyroxene is Wo₁₁En₅₃Fs₃₆. In general, there is a decrease Al/Ti, Cr, and Ti in the sequence: "clots" - sector zoned phenocrysts - matrix pyroxenes.

The high Cr content of these lavas sets them apart from the bulk of the Keweenaw tholeiitic lavas. These unusual lavas record the eruption of what must have been a mush of ferromagnesian "near-cumulate" material to account for the low amount of Al₂O₃. Because both matrix and phenocryst pyroxenes are Cr-rich and have similar compositions, we suggest that these rocks were derived by closed system fractionation from a Cr-rich parent magma.

GRAVITY AND MAGNETIC MODELING OF THE MIDCONTINENT RIFT SYSTEM
IN MINNESOTA AND ADJOINING PARTS OF WISCONSIN

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The Midcontinent rift system of Middle Proterozoic (1,200-1,050 m.y.) age has been the focus of a continuing search for hydrocarbons over the past several years. This exploration activity, together with recent investigations of the structure at the south end of the rift utilizing deep seismic techniques by COCORP, has suggested that it is time to reevaluate structural relationships in Minnesota and adjoining parts of Wisconsin.

The basic structure of the Midcontinent rift system southwest of Lake Superior is envisioned as a central block of basalt flanked by two half-graben basins, filled with sedimentary rocks. The central block, termed the St. Croix horst, is not continuous, but rather is broken into several blocks by left-lateral, northwest-trending faults, believed by some to be of transform origin. The stratified rocks of both sedimentary and volcanic origin are assigned to the Keweenawan Supergroup.

This study involves detailed two-dimensional modeling of gravity and magnetic data along five profiles spaced along the rift system from just south of Lake Superior to the Minnesota-Iowa border. The resulting models from each profile imply that the central horst is a very thick block of mafic material which extends to depths of 15 to 20 km. A flanking basin is well developed along the west side of the rift system in Minnesota where the sedimentary fill is as much as 3 km thick. However the presence of a comparable flanking basin on the east side of the rift system is equivocal. In parts of northwestern Wisconsin no Keweenawan sedimentary rocks have been identified outboard of the horst. Somewhat farther to the south, Keweenawan sedimentary rocks apparently overlie the much older Barron Quartzite, but the younger rocks must be relatively thin as evidenced by windows that expose the quartzitic rocks. Our ability to distinguish the quartzites and the Keweenawan sedimentary rocks on the basis of gravity and magnetic properties is limited, but we suggest that the deep gravity low of the eastern flanking basin in western Wisconsin in part reflects the presence of thick quartzites and crustal downwarp rather than Keweenawan sedimentary rocks.

Conventional geologic interpretations have emphasized the symmetry of the rift system in Minnesota and Wisconsin and have suggested that the St. Croix horst is a simple, fault-bounded block that was uplifted relative to the rocks of the flanking basin(s). However our studies imply that uplift had very little to do with the development of the central basalt blocks. Apparent displacements on the bounding faults are relatively small compared to the overall structural evolution of the rift. Therefore we infer that the rift, throughout most of its development, was the focus of mafic volcanism. We also suggest that as the volcanic system cooled, isostatic adjustment occurred that involved the rotation of the central block on listric faults very much like those recognized in other rift systems of the world.

The geometry of the rift system in southeastern Minnesota is complicated by the presence of northwest-trending vertical faults. The latest motion on these faults is dominantly vertical with northeast side up, but the faults may have had a major strike-slip component early in the history of the rift. Our modeling of this feature is equivocal. The asymmetry of the model implies that basalts are present at depth, and that they formed in a half-graben basin, flanked on the west by a major fault. This structural configuration does not resemble the rift either to the north or to the south. Thus, although a fault can be identified, the major question remains as to whether it was a transform fault, a simple vertical fault, or both.

Magnetic Survey Across the Niagara Fault in Northern Wisconsin,
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The southwest-northeast trending Niagara fault is located in northern Wisconsin and separates two geophysically unique terranes: 1) a Superior craton complex to the north consisting of granite-greenstone and 2) a possible volcanic-arc complex to the south consisting predominantly of gneiss.

The study area is located in Vilas, Forest, Florence and Oneida counties in northern Wisconsin and Iron and Gogebic counties in upper Michigan specifically within the latitudes of 46°15'N and 45°45'S and longitudes of 88°25'E and 89°20'W. Ten north-south roads serving as profile lines were chosen to traverse the Niagara fault perpendicular to strike. The profiles extend approximately ten to twelve miles on either side of the fault and span the forty mile wide study area giving an average distance of four miles between profile lines. Work has been completed along four of the ten roads within the study area using two proton precession magnetometers to obtain field readings every .1 mile.

Four north-south cross sections have been prepared from the magnetic profiles. The cross sections provide information on the magnetic values of the two geophysically unique terranes separated by the Niagara fault and depth and size estimates of crystalline basement structures. Initial magnetic results indicate a higher regional trend south of the fault when compared to the magnetic results north of the fault.

ARE KOMATIITES ARCHEAN MANTLE PLUME PRODUCTS? HOT SPOT ORIGIN
AND EVOLUTION - ARCHEAN AND PHANEROZOIC COMPARED

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Komatiites (high MgO, high melting-T extrusive ultramafic melts) occur at restricted intervals during the Archean and early Proterozoic in all regions of preserved ancient crust. They are restricted areally as well as temporally, suggesting that a special environment was required for their formation. Komatiite bearing successions grade laterally and vertically into tholeiitic or 'MORB'- type volcanic successions.

Their temporal distribution corresponds to peaks in radiometric dates which reflect times of addition of material to the continental crust. Analogous age peaks in the late Proterozoic and Phanerozoic correspond to episodes of new Wilson Cycle origin (Wilson, 1966; Worsley et. al., 1984, 1985; Nielsen 1984, 1985). Phanerozoic hot spot magmatism is characterized by alkali-ultramafic melts produced at depths of ~200 km (Le Bas, 1980). Archean hot spots would have produced komatiites at depths of 150-200 km rather than alkali-ultramafic melts because of a higher geotherm and a mantle solidus that was closer to the surface. Takashi & Scarfe (1985) have shown experimentally that an ascending diapir of peridotite (mantle plume) would generate komatiitic liquids by large scale partial melting at the required depths in the presence of a higher (Archean) geotherm.

The role of mantle plumes or hot spots in the evolution of the continental lithosphere has been outlined by Nielsen (1984, 1985). The interaction of a series of linked or en echelon hot spots is to rift the continental lithosphere and generate the opening of a new ocean basin. The increased rate of ocean crust production must, perforce, increase the rate of consumption elsewhere on the earth. Increased rates of subduction produces greater amounts of second cycle melting which yield granitoid products (continental crust components).

The contrast between Archean and early Proterozoic tectonic styles and magmatic products and those characteristic of the late Proterozoic and Phanerozoic is a result of the different mechanical and material properties of the lithosphere resulting from a higher geotherm and a hotter, thinner, more ductile lithosphere.

Le Bas, M.J., 1980, Alkaline magmatism and uplift of continental crust, Proc. Geol. Assoc. London, 91, 33-38.

Nielsen, P.A., 1984, Episodic global thermo-tectonic events - lithosphere response to precipitation in the outer core, EOS, 67, 272.

Nielsen, P.A., 1985, Hot spot origin and evolution: Archean and Mesozoic compared, EOS, 66, 150.

Worsley, T.R., Nance, D., and Moody, J.B., 1984, Global tectonics and eustacy for the past 2 billion years, Marine Geology, 58, 373-400.

Worsley, T.R., Moody, J.B., and Nance, D., 1985, Proterozoic to recent tectonic tuning of biogeochemical cycles, in The Carbon Cycle and Atmospheric CO₂: Natural Variations, Archean to Recent, edited by E.T.Sundquist and W.S. Broecker, Geophysical Monograph Series, 32, 561-572.

Takashi, E., and Scarfe, C.M., 1985, Melting of peridotite to 14 GPa and genesis of komatiite, Nature, 315, 566-568.

Wilson, J.T., 1966, Did the Atlantic close and then re-open, Nature, 211, 676-681.

METAMORPHISM OF THE DUNBAR GNEISS AND ASSOCIATED SUPRA-CRUSTAL
ROCKS: NORTHEASTERN WISCONSIN, USA

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Restricted basin sediments enriched in sulfides (py+po+cpy) and carbonaceous matter, assigned to the Quinnesic Formation (Dutton, 1971), crop out in northeastern Wisconsin on the north-western margin of the Dunbar dome. Metamorphic grade varies across the structure and decreases away from the contacts with the Dunbar Gneiss and its late stage intrusive components. The Quinnesec Formation is dominantly mafic to felsic volcanics and volcanoclastics (Schulz, 1984). These restricted basin sediments have been explored for massive sulfide mineralization. Their high sulfide and carbonaceous contents have resulted in a poor outcrop record, but samples have been investigated from several drill cores from the West Bass Lake area of Florence County provided by the Kerr-McGee Corporation.

These supra-crustal rocks and the Dunbar Gneiss record similar sequences of fabric development and late stage vein emplacement.

The supra-crustal sequence is characterized by prograde metamorphic assemblages which include:

- 1- diopside - tremolite - calcite + quartz in marbles.
- 2- garnet - hornblende - plagioclase + quartz in metabasalts and,
- 3- biotite - garnet - plagioclase - quartz + cordierite in meta-sediments

Late stage re-equilibration is imposed on most samples. These include the following retrograde alterations

- 1- Plagioclase → epidote + albite
 - 2- hornblende → biotite + actinolite + chlorite
 - 3- cordierite → pinite + sericite
- and
- 4- garnet → biotite + chlorite

Beds enriched sulfide minerals show a loss of Fe from the silicate phases due to sulfidation reactions. The supra-crustal sequence and the Dunbar Gneiss are cut by late stage pegmatites and quartz-tourmaline veins.

In thin section, an S_1 foliation defined by biotite is parallel to bedding planes (S_0). Retrograde biotite (reactions 2 and 4) defines a weak S_2 foliation which is inclined to S_1 by up to 90° . Deformation of the Quinnesic Formation and correlative supracrustals probably corresponds to D_2 and D_4 (Sims et al, 1984) in the Dunbar dome.

The prograde metamorphic assemblages restrict peak metamorphic conditions to $500-550^\circ\text{C}$ at low to intermediate lithostatic pressure (less than 4-5 kbar). Based on the abundance

of carbonaceous matter and sulfides in many core samples,
 $P_{H_2O} < P_{total}$ and CO_2 and H_2S were (at least
locally) major components in the fluid phase.

The Dunbar Gneiss ranges in composition from granite-granodiorite to biotite tonalite and locally contains abundant mafic inclusions (Schulz et al, 1984). In many outcrops, the gneiss grades into migmatite.

The similarity between the deformational and metamorphic histories of the restricted basin supracrustals correlative with the Quinnesec Formation and the Dunbar Gneiss suggests that they were co-eval. The lower metamorphic grade recorded in the Quinnesec Formation is attributed to a smaller extent of erosion due to higher density. The core of the Dunbar dome was formed at the peak of metamorphism by bouyant emplacement of the hotter and lower density Dunbar Gneiss. The time required to form the Dunbar Gneiss protolith, the Quinnesec Formation, and their deformation and metamorphism was on the order of 30 million years (Sims et al, 1984).

Dutton, C.E., 1971, Geology of the Florence Area, Wisconsin and Michigan, U.S.G.S Professional Paper 633

Schulz, K.J., 1984, Volcanic rocks of northeastern Wisconsin, in: Guide to the Geology of the Early Proterozoic Rocks in Northeastern Wisconsin, Field Trip 1, Thirtieth Annual Institute on Lake Superior Geology, p. 51-81

Schulz, K.J., Sims, P.K., and Peterman, Z.E., 1984, Geochemistry of the Dunbar Gneiss Dome, N.E. Wisconsin, in: Guide to the Geology of the Early Proterozoic Rocks in Northeastern Wisconsin, Field Trip 1, Thirtieth Annual Institute on Lake Superior Geology, p. 24-42

Sims, P.K., Peterman, Z.E., and Schulz, K.J., 1984, Dunbar Gneiss - Granitoid Dome, in: Guide to the Geology of Early Proterozoic Rocks in Northeastern Wisconsin, Field Trip 1, Thirtieth Annual Institute on Lake Superior Geology, p. 1-23

ANALYSIS OF A RECENT SEISMIC REFLECTION AND GRAVITY PROFILE ACROSS THE MIDCONTINENT RIFT

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A recent seismic reflection and gravity profile crosses the Midcontinent rift at a latitude of $45^{\circ} 25'$ N. Stacking velocities obtained from the seismic data were used to convert travel times to approximate depths to basement for the basins flanking the rift. Comparison with analysis of the COCORP line in Michigan (Brown et al., 1982) facilitated interpretation of the seismic data. Reflecting horizons representing lava flows, Precambrian sediments, and Paleozoic sediments have been tentatively identified.

We have modeled the shape of the basement reflector using plate flexure theory. The flexural model approximates the crust and lithosphere as a ruptured elastic plate floating on an inviscid fluid and loaded on the end by an infinite strip running along the rift axis. While the lack of accurately dated sediment horizons precludes time dependent modeling of the evolution of the rift and the subsidence leading to the formation of the sedimentary basins, the static deformation predicted by thin plate theory provides a reasonable fit to the seismic data (Figure 1.). The magnitude of the load required to produce the deformation is consistent with intruded magma, surface basalts and thermal contraction of a thinned lithosphere.

The flexural profile formed the basis for a gravity model. Sediments filled the depression created by lithospheric flexure and produced the negative anomaly flanking the rift axis and the load causing the flexure produced a central positive anomaly. Agreement between the calculated and observed anomalies provides an independent verification of the model.

Brown, L., L. Jensen, J. Oliver, S. Kaufman and D. Steiner, 1982:
Rift structure beneath the Michigan basin from COCORP
profiling. *Geology*, v. 10, p. 645-649.

BASEMENT PROFILE

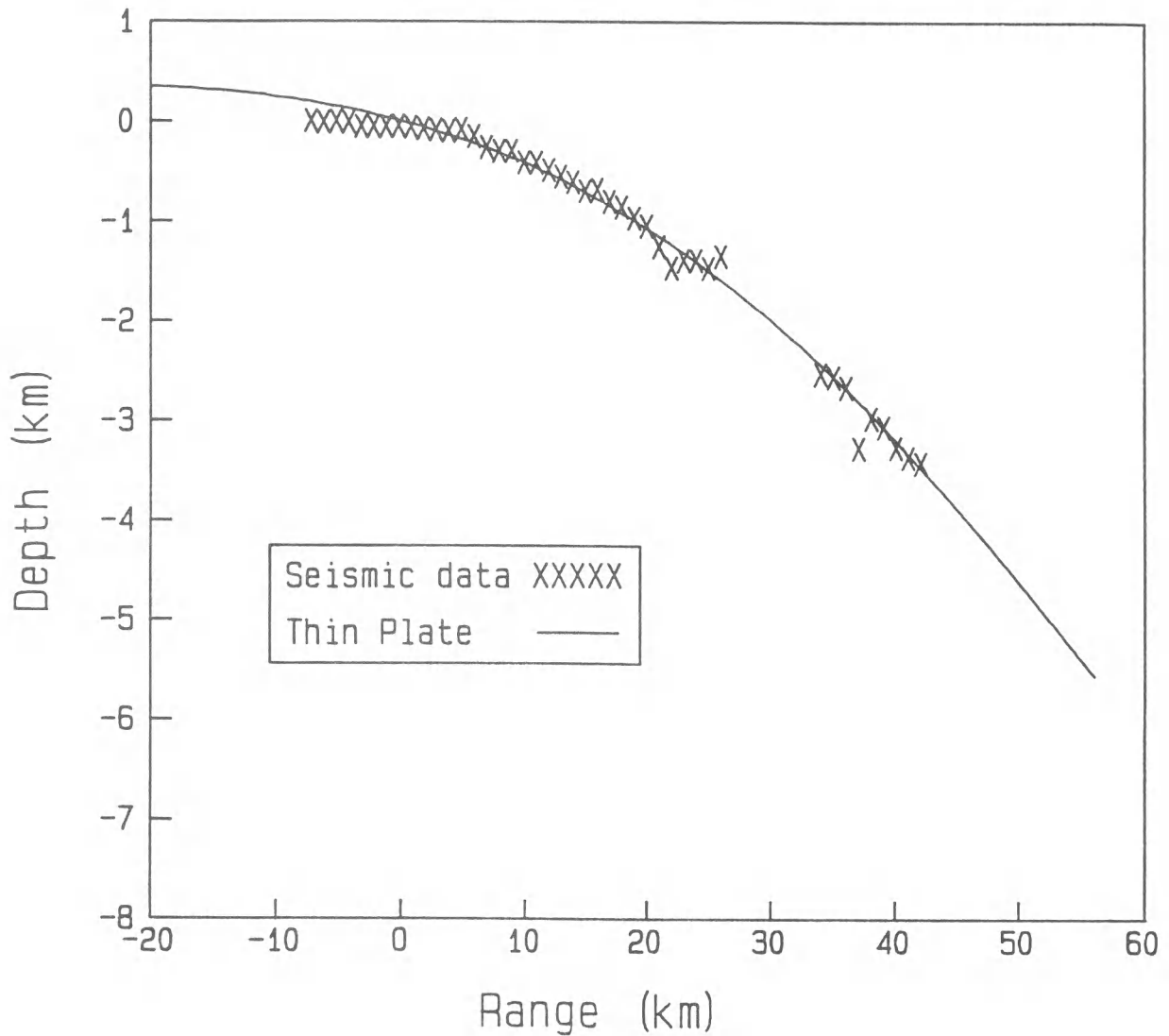


Figure 1. Plotted are depths to basement for the Western basin calculated from seismic reflection data and the deformation given by thin plate theory for a semi-infinite plate with an end load.

MINERALOGY AND CHEMISTRY OF THE FERRODIORITE OF THE
MINERAL LAKE INTRUSION, MELLEN, WISCONSIN

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Major and rare earth element (REE) data from the Mineral Lake intrusion support earlier petrographic and mineralogical studies that indicate the ferrodiorite is a product of olivine and plagioclase fractionation. Enrichment of Fe, Ti and P observed in major element analyses, paralleled by enrichment of light REE, support the fractionation hypothesis. Recent anomalous Rb/Sr isotopic data, however, suggest that the ferrodiorite composition may be influenced through contamination by older crustal rocks or may be a magma that is unrelated to the Mineral Lake Intrusion.

Recent studies of the mineralogical and chemical nature of the ferrodiorite indicate several changes that occur across the belt from south to north; upward in the intrusion. 1. It is systematically differentiated with its most Fe-rich mafic phases to the north. (Cpx=Wo₃₉En₃₅Fs₂₆ to Wo₃₉En₂₂Fs₃₉; Opx=Fs₄₆ to Fs₆₉; Ol=Fa₇₇ to Fa₈₅) 2. Plagioclase becomes more sodic. (Cores=An₅₂ to An₃₀; rims=An₄₈ to An₂₉) 3. Both amphiboles and alkali-feldspar appear in the modes and become more abundant to the north grading to rocks of more felsic composition.

Application of the Lindsay two-pyroxene thermometer at one atmosphere pressure indicates a temperature range of 850-750°C, for the above compositions. Some fine exsolution was observed so these should be taken as minimum temperatures. Fe-Ti oxide geothermometry generally yields lower temperatures (520-610°C) but one oxide pair yielded a temperature of 1035 ± 25°C and log fO₂ of 9.2 ± 0.2. This last value compares well with magmatic conditions determined for Kilauea lava lake. Two amphiboles, hornblende and a cummingtonite, along with biotite and alkali feldspar, which replaces plagioclase, are common in the rocks higher in the belt. The presence of hydrous phases indicates an increase in pH₂O in the more felsic rocks. These mineralogical factors along with the evolved rock composition and close spatial relationship to the underlying anorthosite of the Mineral Lake Intrusion support the hypothesis of an origin by evolution of a magma of basaltic composition through fractional crystallization.

GEOCHEMICAL CYCLICITY AND MAGMA EVOLUTION WITHIN THE PORTAGE LAKE VOLCANICS FLOOD BASALT SEQUENCE, UPPER MICHIGAN

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The Keweenaw Portage Lake Volcanics (PLV) represents the youngest exposed continental flood basalt basin associated with the aborted Midcontinent Rift. Logging and sampling of 11 drill holes across a representative 4.6 km section reveals a succession of over 220 individual lava flows consisting of aphyric, high-Al, Mg- to Fe-rich olivine tholeiites with only minor more-evolved quartz tholeiites and icelandites. Twenty to thirty interflow sedimentary horizons are scattered throughout the volcanic pile and represent significant hiatuses of lava extrusion.

Major and trace element analyses of 150 lava flows indicate a complete geochemical continuum as opposed to two distinct magma types. PLV magmas are collectively more-primitive (higher Mg' and Ni contents; lower LIL element contents) than both magmas within older basins associated with the Midcontinent Rift as well as other continental tholeiites. Major element compositions of the PLV are similar to MORB but generally contain higher incompatible trace element contents. Rare earth elements exhibit smooth, slightly LREE-enriched ($\text{La/Sm} = 3$) patterns with La abundances of 15x-140x chondrites. These patterns remain parallel for all compositions from primitive olivine tholeiites (slightly positive Eu anomalies) to most-evolved icelandites (slightly negative Eu anomalies). Bivariant plots of incompatible trace elements exhibit simple, highly-correlated linear relationships with near-zero intercepts.

Strato-geochemical plots reveal several scales of overall and oscillatory variation which monitor the magmatic evolution of the system (Figure 1). From base to top of the section, PLV magmas show an overall trend of liquid compositions which become more primitive with time. Superimposed on top of this overall trend are three major oscillatory geochemical cycles which exhibit trends progressing from less- to more-primitive compositions. Major cycles contain between 60 to 80 flows with a cumulative thickness of 1200 to 1500 m. Numerous minor cycles, which exhibit more- to less-primitive trends, are superimposed on top of the major cycles. Minor cycles contain 2 to 10 flows comprising a cumulative thickness of 50 to 200 m. The culmination of minor cycles are strongly correlated to the occurrence of interflow sedimentary horizons, however major cycles are not marked by any such geologic event.

Cummulative geologic and geochemical evidence suggests that these mantle-derived basaltic magmas were not significantly modified by processes of crustal contamination. Major element CMAS phase relations imply that liquids equilibrated at high pressure (15-20 kb) with solid phases dominated by olivine and

plagioclase. More- to less-primitive minor cycles can be modelled by fractional crystallization involving mostly olivine and plagioclase only in an open system in order to maintain higher-than-predicted compatible elements and lower incompatible elements for a given degree of fractionation. Less- to more-primitive major cycles as well as the overall trend towards more-primitive compositions are most likely controlled by progressively increasing the degree of partial melting or the rates of magma production and extrusion. Our working petrogenetic model involves a complex combination of processes to explain the chemical variations observed in PLV magmas, including: 1) varying degrees of partial melting in a single, homogeneous mantle source with non-depleted LREE and 2) crystal fractionation and magma mixing in periodically replenished, sub-crustal magma chambers.

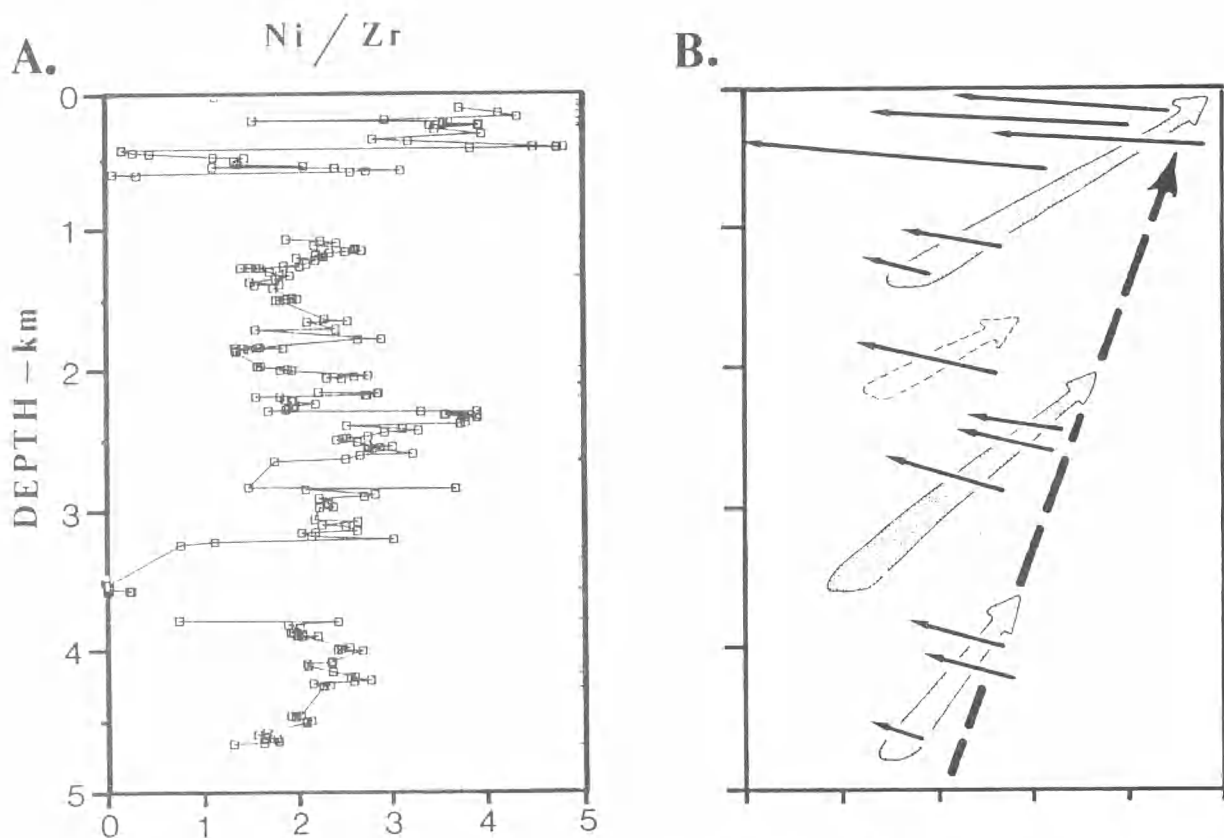


Figure 1. A. Typical strato-geochemical relationships for PLV magmas. Ratios of immobile elements allow even moderately altered lavas to reflect changes in primary compositions. Ni/Zr monitors the degree of magma evolution with primitive lavas containing the highest ratios.

B. Interpretation of geochemical variations with depth based on A. Dashed arrow represents the overall compositional trend while large stippled arrows indicate major cycles and small solid arrows indicate minor cycles.

SPECULATIONS ON THE OIL AND GAS POTENTIAL OF KEWEENAWAN MIDCONTINENT RIFT SYSTEM IN NORTHWESTERN WISCONSIN

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Extensive leasing and seismic exploration along the Keweenaw Midcontinent Rift System from Upper Michigan into Kansas centered in northwestern Wisconsin in 1984 - 1985. Detailed geochemical and geophysical justification for this petroleum play remains confidential, but regional geology allows generalized speculation.

Continental rifting with extrusion and intrusion of igneous rocks caused subsidence in northwestern Wisconsin, and 3800 m of Upper Keweenaw conglomerate, shale, and sandstone accumulated to form the Oronto Group (Copper Harbor Conglomerate, Nonesuch Formation, and Freda Sandstone). These slightly metamorphosed rocks are dominantly red beds deposited as alluvial fans grading upward into finer, texturally and mineralogically more mature, lacustrine and fluvial deposits. After 50 to 90 km of separation, the rift failed and axial uplift created the St. Croix horst with subsiding flank basins. Up to 2000 m of sandstone with some shale (Bayfield Group) accumulated adjacent to the eroding horst.

Shale and siltstone of the Nonesuch lie between potential reservoir rocks, and contain sufficient organic matter that oil seeps occur within the formation in Upper Michigan. As the only source rock and the most continuous seal, the persistence of this unit is critical to petroleum potential. A somewhat flawed analogy with giant oil and gas fields in Siberia, U.S.S.R., provides additional support. Possible traps include anticlines, reverse faults with upthrown basalt seals, truncation against highs, porous lenses, and an angular unconformity.

Keweenaw petroleum potential is heightened by inexpensive leases for large tracts, relatively cheap drilling in a politically stable area, and the potential for discovering gas storage. Wisconsin, however, has high taxes and strong environmental laws, and drilling in Lake Superior would be prohibited even if a lakeside field were discovered.

Due to current economics of the petroleum industry, exploration interest has waned, and drilling in this high risk area is not anticipated in the near future. Although Amoco cancelled a 1985 wildcat in Bayfield County that would have evaluated the St. Croix horst, a new 4 million dollar rift test in western Carroll County, Iowa will supposedly be drilled in 1986. If successful, interest in northwestern Wisconsin would be rekindled.

Penokean(?) Ductile Shear Zones in Archean Metadiabase Dikes:
Evidence of Stress Reorientation by Basement Inhomogeneities,
Marquette Range, Michigan.

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The regional setting of our study area is within the late Archean Northern Greenstone-Granite Terrane of the Great Lakes Tectonic Zone. Specifically, we are focusing on three localities along the Lake Superior shore north of Marquette, Michigan. Two of these specific study areas include ductile shear zones (NW $\frac{1}{4}$ sec. 33, T.49 N., R.25 W., less than a mile SE of Sugarloaf Mountain). The country rock in this area consists of the Compeau Creek Gneiss (2.6-2.8 b.y.). The first ductile shear zone is exposed on a small island near the shore and occurs within a meter wide metadiabase dike striking N 20°W. A small pegmatite dike perpendicularly crosses this dike and is heterogeneously sheared across the zone with a right-lateral displacement of approximately 5 meters. The stretched and detached pegmatite marks and integrates the varying degrees of strain across the ductile shear zone. Card deck simulation shows maximum strain ellipticity values (R) of 9.5 at the center of the zone with minimum values of 3.8 near the borders of the zone. Measurements taken from our map of the dike reveal maximum shear strain values (γ) of -3.5 near the center and a minimum of -1.3 near the borders, corresponding to angular shear values of -74° and -39°, respectively. North of this island along the shoreline, the second ductile shear zone also exhibits right-lateral movement. This zone, found in a half-meter wide metadiabase dike striking N76°W. has no markers to permit determination of the actual displacement value. The third locality, Granite Point in T.49 N., R.25 W., shows ductile deformation of granitic dikes (probably Compeau Creek Gneiss-"granite" material) within a layered amphibolite country rock (probably Mona Schist). The maximum shortening is in a N-S direction.

The deformational history of our study area has regional tectonic implications. The Compeau Creek Gneiss of the Sugarloaf shoreline was emplaced in at least three stages. An extensional episode, following cooling, is implied by the WNW dominant strike of diabase dike swarms in the Marquette 7 $\frac{1}{2}$ minute quadrangle. Right-lateral movements in the heterogeneous ductile shear zones are consistent with a N-S shortening. This N-S shortening is also evident at Granite Point. We suggest that this strain may be related to the development of the Late-Archean Great Lakes Tectonic Zone or a deep-seated ductile strain associated with the 1.9 b.y. Penokean tectono-thermal event. Both events have previously been described as showing N-S shortening. In either case, stress reorientation has occurred and movement was guided and localized along favorably oriented dikes.

AN AEROMAGNETIC STUDY OF THE ROCK ELM
STRUCTURE - PIERCE COUNTY, WISCONSIN

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The Rock Elm structure is a cryptoexplosion site located in east Pierce County in west-central Wisconsin. The site is on the southern edge of the Canadian shield which is overlain by Cambrian and Ordovician shallow marine sediments. The structure is roughly circular with a diameter of approximately 6 kilometers. Sediments within the structure are bounded by faults with a downward displacement of 50 meters. The structure also contains a central uplift with a zone of brecciation. Stratigraphic and fossil evidence place the age of the structure at lower to middle Ordovician (Cordua, written communication, 1985).

During the Fall of 1985, UW-Oshkosh conducted an aeromagnetic survey of the Rock Elm structure. The survey covered four 15-minute quadrangles consisting of 53 flight lines, orientated north-south. The flight lines, navigated by Loran C, were flown on half-mile spacings, 1800 feet above sea level. The data were collected with an on-board computer acquisition system and were stored on magnetic tape. Data processing included: post-flight low-pass filtering of the Loran C coordinates using a 13-point digital filter; interpolation of the magnetic data to 1024 equally-spaced points; and regional and heading error corrections.

To enhance small anomalies in the presence of large ones an automatic gain control function, similar to power expansion in seismic data processing, was applied to a zero-phase bandpassed version of the data.

The Rock Elm aeromagnetic data suggests that the structure is located at the site of a highly faulted basement. The similarity of this occurrence with the same fault relationships at the Slate Islands in Lake Superior, another cryptoexplosion site, leads us to consider — as a working hypothesis — that these two sites may be the result of mantle plumes rupturing zones of crustal weakness.

Strain Models for the Evolution of the
Vermilion District, Minnesota

by

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The Vermilion District of northeastern Minnesota is an east-west-trending Archean greenstone belt comprising volcanic and sedimentary rocks. This belt is bounded to the north by a major dextral strike-slip fault, the Vermilion Fault. Higher-grade rocks occur to the north and south of the district. More than 50 strain measurements have been made in rocks distributed throughout the district. A coherent deformation history is indicated by these strain patterns, which can be analyzed both by inferring a pre-tectonic configuration from the strain data and by constructing a model sequence of strains to reproduce the observations.

An analysis of strain patterns in the Vermilion District must explain the following features. East-west-trending belts of common strain symmetry vary from primarily flattening in the north to constrictional in the south. Maximum elongations (X) of the constrictional strains consistently plunge between 30° and 60° to the east. Flattening strains have steeper east- or west-trending plunges for X . The maximum shortening axes (Z) are consistently oriented north-south and subhorizontal. Several characteristics of the rocks imply origin by dextral shear, especially to the north as the Vermilion Fault is approached. Such features include dominantly Z asymmetry of folds, schistose zones crossed by shear bands, and ductile shear zones with sigmoidal foliation patterns.

I have programmed a three-dimensional finite element method to spatially integrate the distributed strain measurements. The best fit between unstrained elements includes the rotations and translations which cannot be found directly by measuring strained clast and particle shapes. The resulting pre-tectonic configuration implies approximately 41% shortening in the north-south direction, assuming no volume change. Flattening strains increase to the north, and samples near the present Vermilion Fault rotate in a dextral sense. No large rotations are implied in the vertical direction, as would be in the case of shear off the flanks of a rising diapir. Rotation of the metasediments around a steeply-plunging anticlinal core of relatively rigid greenstone is implied at the eastern end of the district. Homogeneous constrictional strains dominate to the west and south.

The strain values, orientations, and distribution can be broadly reproduced using several models. The above observations place strong constraints on the generally infinite number of paths that can lead to these finite strains. If homogeneous constrictional finite strain is used as a starting point, a subsequent superposed dextral simple shear of variable magnitude fits the observations with an assumption of constant volume. The model uses a north-dipping shear plane, striking east with a subhorizontal shear direction. As simple shear increases, the strain changes from constrictional to flat-

tening and the plunge of X changes from east to west. This shear direction is consistent with the east-trending zones of common strain symmetry. East-trending ductile shear also correlates with late-stage brittle shear now shown by the ESE-trending Vermilion Fault for the same stress orientation. Similar variations of finite strain can be produced by a continuous sequence of incremental strains combining a steadily decreasing constriction component with variable amounts of an increasing shear component.

The constrictional strains used as a starting point in the model above could result from a moderate anticlockwise reorientation of the shear direction in a transpressively flattened rock. The X-axis would then rotate into an orientation of incremental shortening and produce a large, steeply plunging constrictional zone. Anastomosing juxtaposed zones of flattening and constriction can be constructed geometrically to give a bulk homogeneous strain combining N-S flattening and dextral shear. These patterns are difficult to describe analytically, but could also explain how zones of constriction can occur in such an overall transpressive strain regime.

The simple shear components of the deformation indicate the Vermilion District was a softer zone deformed between more rigid blocks to the north and south, analogous to shear zones commonly seen on a smaller scale. The observational constraints and the strain models outlined here are consistent with strongly oblique horizontal convergence and shear.

Precambrian basement map of the northern midcontinent

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A new compilation of data from about 1,500 drill holes to basement in the northern midcontinent (area bounded by 36°-46° N. Lat. and 88°-100° W. Long.) has been prepared as part of a cooperative federal-state project. The map was compiled at a scale of 1:1,000,000 (Sims, 1985) from 1:500,000-scale maps submitted by respective state geological surveys showing locations of basement drill holes, rock types penetrated in the holes or sketchy geologic map units, and basement topography, contoured at 200-foot intervals. The map updates the "Basement rock map of the United States" (Bayley and Muehlberger, 1968) for this region.

Because of the availability of generally high quality regional aeromagnetic (Zietz, 1982) and gravity (Hildenbrand, 1982; Simpson and others, in press) anomaly maps and substantial reliable isotopic age data, we attempted for the first time to actually delineate broad geologic rock units in the basement. In a sense, the map is a predictive model that can be tested as more geologic and geophysical data become available.

The northern midcontinent region includes the southernmost exposed Precambrian of the Canadian Shield and the buried basement of the interior platform. Structurally, it is part of a continent-wide "tectonic collage" consisting of (1) Archean cratons (>2500 Ma) and remnants of Early Proterozoic cratonic cover, (2) anastomosing Early Proterozoic orogenic belts, which partly enclose and marginally affect the Archean cratons, and (3) intracratonic igneous and sedimentary rocks, mainly of Middle Proterozoic age but including a ~1760 Ma rhyolite-granite terrane and scattered quartzite of the "Baraboo interval" (Dott, 1983).

The principal geologic contribution resulting from the compilation is delineation of a major buried, east-trending Early Proterozoic orogen (1.63-1.80 Ga), named the Central Plains orogen (Sims and Peterman, 1986). It extends across Nebraska and Kansas into Missouri, and is correlated with the Early Proterozoic foldbelt exposed in the basement uplifts in Colorado and southern Wyoming. This orogen truncates the older Penokean (~1.83-1.90 Ga) and Trans-Hudson (1.85-1.95 Ga) orogens, as well as the southern margins of the Superior and Wyoming Archean cratons (fig. 1).

References cited

- Bayley, R. W., and Muehlberger, W. R., compilers, 1968, Basement rock map of the United States, exclusive of Alaska and Hawaii: U.S. Geological Survey, 2 sheets, scale 1:2,500,000.
- 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.
- Hildenbrand, T. G., Simpson, R. W., Godson, R. H., and Kane, M. F., 1982, Digital colored residual and regional Bouguer gravity maps of the conterminous United States with cut-off wavelengths of 250 km and 1,000 km: U.S. Geological Survey Geophysical Investigations Map GP-953A, scale 1:7,500,000.
- Simpson, R. W., Jachens, R. W., Blakely, R. J., and Saltus, R. W., in press, First vertical derivative of isostatic residual gravity map: U.S. Geological Survey, scale 1:7,500,000.
- Sims, P. K., 1985, Precambrian basement map of the northern midcontinent, U.S.A.: U.S. Geological Survey Open-File Report 85-0604, scale 1:1,000,000.
- Sims, P. K., and Peterman, Z. E., 1986, Early Proterozoic Central Plains orogen: A major buried structure in north-central United States: *Geology*, v. 14.
- Zietz, Isidore, 1982, Composite magnetic anomaly map of the United States, Part A, Conterminous United States: U.S. Geological Survey Geophysical Investigations Map GP-954A, scale 1:2,500,000.

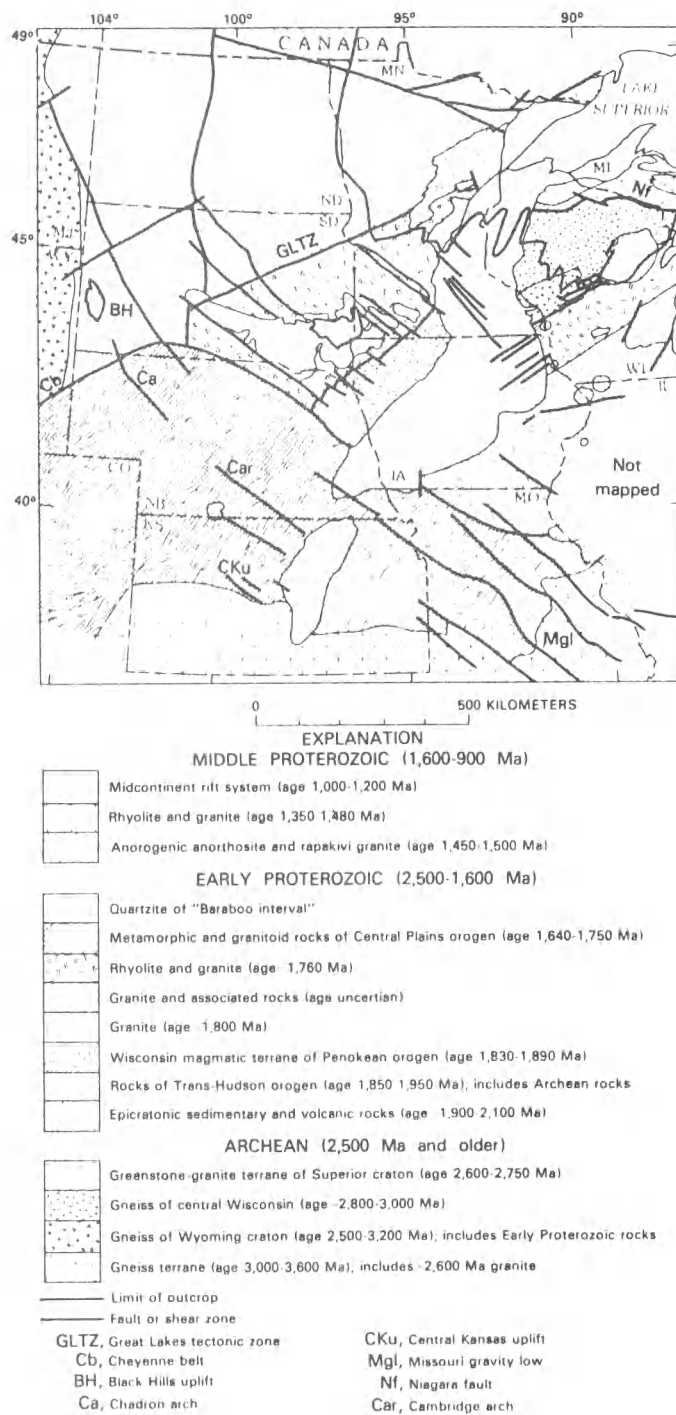


Figure 1. Precambrian basement map of north-central United States. Modified from Sims, 1985.

A Gravity Survey Over The Waukesha Fault In Southeastern Wisconsin, Sverdrup, K.A., and W.F. Kean, Department of Geological and Geophysical Sciences, University of Wisconsin-Milwaukee, Milwaukee, WI 53201

A gravity survey covering roughly 1500 square miles was conducted on a 1 mile square grid across the Waukesha fault in Waukesha, Washington, Ozaukee, and Milwaukee counties. The resultant calculated Bouguer anomaly map clearly indicates the presence of the fault striking approximately N40E and extending for about 40 miles from Waukesha, WI to the Lake Michigan shoreline. The amplitude of the Bouguer anomaly across the fault is as large as 12 milligals in some areas.

Preliminary modeling of the structure indicates that the fault is probably a high angle growth fault downthrown to the southeast. The throw on the fault appears to be as little as 40 feet in the Niagaran dolomite near the surface and possibly in excess of 2000 feet in the Precambrian basement.

A PRELIMINARY STUDY OF REGIONAL METAMORPHISM IN EARLY PROTEROZOIC ROCKS NEAR MOUNTAIN, WISCONSIN

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Early Proterozoic rocks in the Mountain area include the Waupee volcanics, Macauley gneiss, Hines quartz diorite, Baldwin conglomerate and at least two generations of mafic dikes. Lahr (1972) subdivided the Waupee volcanics into three units based on their protolith. The Lower unit is composed of massive porphyritic lava flows and hornblende rich metasedimentary rocks. The middle unit consists of feldspathic to quartz rich metasedimentary rocks. The Macauley gneiss is a metamorphosed plutonic rock ranging in composition from a quartz monzonite to a granodiorite which Lahr (1972) divided into the Macauley gneiss and Macauley gneiss border zone. The more mafic border zone was interpreted by Lahr to represent a contaminated zone of the Macauley gneiss. The Hines quartz diorite is a later intrusive that shows a well preserved igneous texture. The Baldwin conglomerate is a metaconglomerate that contains pebbles of the Macauley gneiss and the Waupee volcanics. At least two generations of mafic dikes occur in this area. One of the younger dikes, which locally exceeds a thickness of 3m was not recognized by previous workers.

The Early Proterozoic rocks in this area show two metamorphic mineral assemblages. The oldest assemblage represents an amphibolite facies regional metamorphic event which occurred prior to the intrusion of the Wolf River batholith (1500 Ma). This episode of regional metamorphism is characterized by isoclinal folding, development of an S_1 foliation and intrusion of granitic plutons (border zone) which may have emplaced older gneissic basement (Macauley gneiss). S_1 is an axial planar foliation which formed as a result of folding and rotation of bedding in the Waupee volcanics and a foliation in the Macauley gneiss. Evidence for transposition includes small scale isoclinal folds and crossbedding-like structures which have been folded by a later open folding event. The younger assemblage is upper greenschist facies and may have formed as a result of either hydrothermal metamorphism by the Wolf River batholith or an earlier regional metamorphic event that is evidenced by an S_2 foliation. S_2 is observed in the Baldwin conglomerate that unconformably overlies volcanic and plutonic rocks deformed and metamorphosed during the first event. The S_2 foliation in the Baldwin conglomerate has a similar trend to axial surfaces in the Macauley gneiss and Waupee volcanics and has augen shaped pebbles aligned parallel to the foliation. The first episode of regional metamorphism has been previously interpreted to be a result of the Penokean orogeny (1835 Ma) which is characterized by greenschist facies metamorphism and intrusion of granitic plutons. The presence of an amphibolite facies mineral assemblage raises the question that the volcanic sequence in the Mountain area may be older than greenschist facies volcanic rocks typically associated with the Penokean orogeny. Table 1 (next page) summarizes a tentative geologic history for the area.

PRECAMBRIAN ROCKS OF NEBRASKA

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The Precambrian rocks of Nebraska are bounded by Archean and Proterozoic rocks to the north and by Proterozoic, epizonal granites and rhyolites to the south.

A re-examination of all of the cores and cuttings studied by Lidiak (1972) and a study of all of the cores and cuttings produced since the publication of Lidiak's and Carlson's pioneering works indicate that the basement rocks of Nebraska consist primarily of granitic rocks, which range in composition from granite to tonalite. Closely associated with the granitic rocks are older gneisses and schists, which occur as thin screens between small plutons and as broad terrains that separate large areas of granitic rocks, possibly very large composite batholiths, from each other. Zircon ages (Van Schmus et al. in press) indicate these rocks range in age from 1.6 to 1.8 billion years.

These rocks are cut by the younger, granitic rocks of the Red Willow batholith, which has a zircon age of 1.44 billion years (Van Schmus et al. in press); an anorthosite; magnetite-bearing plutons; gabbro plugs, which in southeastern Nebraska have an Ar/Ar age of 1.1 billion years; and the Elk Creek a carbonatite, which has a K/Ar age of 544 million years (Peterman, personal communication). The older rocks and perhaps some of the younger igneous rocks are mantled by quartzite, red clastics, basalt, and rhyolite. The quartzite of northeast Nebraska seems to correlate well with the Sioux. The knobs and patches of quartzite which occur elsewhere in the state frequently contain sillimanite and are not so easily assigned an age. The red clastics and the basalts of eastern Nebraska are clearly Keweenawan in age. Rare and isolated occurrences of basalt and rhyolite also occur but are difficult to correlate.

In light of the small number of zircon ages, sparse chemical data and lack of bore hole data, especially for the northern half of the state, it is difficult to formulate a detailed geologic history of the Precambrian rocks of this area. Data in hand, however, seem to indicate the older rocks were once part of an arc complex that was later intruded by anorogenic granites. Uplift erosion and rifting followed.

Precambrian Evolution of the Northern Midcontinent Region

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Petrographic, geochemical, and U-Pb geochronologic studies of sub-surface samples obtained from drill holes to basement have been combined with interpretation of recent geophysical maps to yield better understanding of Lower and Middle Proterozoic continental basement in the central U. S. The Archean Superior Craton is truncated south of Lake Superior by 1.83 to 1.89 Ga old orogenic suites of the Penokean Province. To the west, the Archean Wyoming Craton is truncated on the south by the Cheyenne Belt and bordered by 1.70 to 1.78 Ga old units of the Colorado Province. Subsurface samples between the Archean cratons and between the Penokean and Colorado provinces indicate general continuity of units about 1.8 Ga old. Data from the southwest U. S. and from midcontinent basement indicate that the 1.7 to 1.9 Ga old orogenic provinces are flanked to the south by igneous and metamorphic rocks 1.6 to 1.7 Ga old. These Lower Proterozoic terranes represent lateral accretion to the south of the Archean cratons. The Lower Proterozoic terranes were intruded by Middle Proterozoic plutons which are the deeper seated manifestations of extensive remobilization of the Lower Proterozoic crust. To the south, the older terranes are covered by large areas of rhyolite and epizonal granite, which are shallower manifestations of the same events. The granite and rhyolite represent two distinct suites, 1.45 to 1.50 Ga and 1.34 to 1.40 Ga old. The older suite is more extensive, extending from California to Labrador; the younger suite is only known from the south-central U. S. Both suites appear to have been derived from partial melting of Lower Proterozoic continental crust. Thus, they represent vertical redistribution of older Proterozoic continental crustal material, rather than lateral growth.

A GRAVITY SURVEY OF THE LAKE MICHIGAMME AREA, MICHIGAN

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A gravity survey was conducted in the region surrounding Lake Michigamme, western Marquette and eastern Baraga Counties, Michigan, to study the relationships between the Precambrian X Marquette Supergroup rocks and the Precambrian W basement rocks at the intersection of the Marquette and Republic troughs.

Three hundred and forty gravity stations were occupied in an area of 380 km² with station spacings varying between 0.1 and 1.0 km. The observed gravity values were Bouguer corrected relative to Champion railroad station (487.1 m) assuming a bedrock density of 2.68 gm/cm³. Elevation control was maintained using two altimeters and topographic maps.

Positive anomalies are associated with the Precambrian X metasedimentary rocks which have a density contrast of 0.22 gm/cm³ relative to the mostly granitic gneiss basement. The dominant positive gravity anomalies thus follow the axes of the three Precambrian X sediment filled troughs. Positive anomalies are also associated with exposures of iron formation along the north shore of Lake Michigamme. There is also a local gravity high over Dutchman's Point (Lake Michigamme).

The subsurface structure was modelled using the method of Talwani et al. (1959) along six profiles: three northwest - southeast, two north - south, and one northeast - southwest. In our favored model, the Michigamme Formation thickens towards the west and may be up to 2 km thick west of Lake Michigamme. Locally, a thickening of the Formation east of Spruce River could be considered to be fault controlled because it occurs along a zone which is an extension of the inferred position (Cannon and Klasner, 1976) of the Michigan River Trough Fault. The Menominee Group rocks (particularly the Siamo slate) are restricted to within several kilometers of the northern edge of the Marquette trough. We interpret the data to indicate that the Marquette trough is asymmetrically shaped and steeply dipping at its northern edge. The relatively constant values of gravity west of Lake Michigamme make it difficult, however, to discriminate between various alternatives which could be proposed.

The basement can be modelled as being a relatively smooth surface and there is no evidence for major discontinuities that would be expected if the troughs were superposed on one another. This suggests that the elongated troughs were formed contemporaneously and not in distinct tectonic episodes.

A PROPOSED FAULT IN ARCHAIC ROCKS NORTH OF VIRGINIA, MINNESOTA--
AN EXTENSION OF THE BIWABIK FAULT?

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Field mapping in the eastern portion of the Giant's Range Complex of northeastern Minnesota points to the existence of a significant northwesterly trending fault in Archaean rocks just north of Virginia. The trace of the fault is marked topographically by a small valley occurring between roadcuts of migmatitic tonalitic gneiss to the north and greenstone to the south along the Laurentian Divide. Evidence for the fault includes the occurrence of a mylonitic zone trending parallel to the trace of the proposed fault in a roadcut of tonalitic gneiss just north of the fault, and brecciation of granitic rocks and extensive quartz mineralization in granitic and adjacent metavolcanic rocks further to the northwest.

Based on previous work by the author (Welsh, 1985) that suggests the southern portion of the Giant's Range Complex to be in fault contact with metavolcanic rocks in the Virginia-Biwabik area, the fault described here is interpreted to be a westward extension of the Biwabik Fault. Sims and others (1970) extended the Biwabik Fault further to the north as the Dark River Fault, basing their interpretation primarily on geophysical information. It is here considered that the proposed extension of the Biwabik Fault is more consistent with present geological and geophysical data.

Although movement along northwesterly trending faults has been described as strike slip, there is no evidence at this stage of the study to suggest strike-slip motion for this fault. Displacement of the Biwabik Iron Formation along the Biwabik Fault east of Biwabik has been recognized as vertical, and obviously of post-Animikian age. However, this age of movement does not rule out the possibility that the Biwabik Fault could be a remobilized Archaean fault. Because this fault cuts through greenstones in the Virginia Horn area, recognition of possible Archaean movement along this fault could prove critical for gold exploration in the area.

References

- Sims, P.K., Morey, G.B., Ojakangas, R.W., and Viswanathan, S., 1970, Geologic Map of Minnesota: Hibbing Sheet: Minn. Geol. Survey.
- Welsh, J.L., 1985, Preliminary investigations into the geology of the Giant's Range Complex, Virginia-Biwabik area, N.E. Minnesota: Ann. Inst. Lake Superior Geol., 31st, Proc., p. 96.

A COMPARISON OF FINITE STRAINS IN QUARTZITES AND SLATES OF THE
MARQUETTE RANGE SUPERGROUP, MARQUETTE COUNTY, MICHIGAN, U.S.A.

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Finite strains measured in quartzite and slate in the Eagle Mills Syncline near Negaunee, Michigan, indicate that flattening was the dominant mode of deformation produced in Marquette Range supracrustal rocks during the Penokean Orogeny. Based on measurements of ellipsoidal reduction spots in the Ajibik Quartzite, a 15 percent flattening sub-parallel to the Marquette Trough is suggested for this formation, as compared to the 50 percent flattening strains measured previously in slates of the Kona Formation (Westjohn, 1978). Ellipse sections based on the Fry method (two dimensional analysis of quartz grain subfabrics) mimic the mean ellipse orientation measured from reduction spots in some cases, but in general, strains based on quartz grain subfabrics indicate bulk strains less than those measured from reduction spots in the Ajibik. The quartzites studied are not equigranular, which may account for the disparity in strain values between methods. Alternatively, the flattening strains measured from reduction spots could have resulted primarily by grain boundary sliding, without significant distortion of individual quartz grains. Based on this new data (finite strain in the Ajibik Quartzite), and on data from a previous study of Kona Formation slates, it is suggested that flattening strains for supracrustal rocks in the Marquette Trough are between the limits of these data, that is less than 50 percent but greater than 15 percent. This deformation style and the observed flattening strains can best be explained by compression related partial closure of the Marquette Trough during the Penokean Orogeny, as suggested by Cambray (1977 & 1978), and perhaps in a "transpressional" tectonic regime similar to the environment proposed by Harland (1971) for the Caledonian Spitzbergen.

References

- Cambray, F.W., 1977, The geology of the Marquette district: a field guide. Michigan Basin Geological Society, 62 p.
- Cambray, F.W., 1978, Plate tectonics as a model for the environment of deposition and deformation of the early Proterozoic (Precambrian X) of northern Michigan [abs.]. Geological Society of America Abstracts with Programs, v. 10, no. 7, p. 376.
- Harland, H.B., 1971, Tectonic transpression in Caledonian Spitzbergen. Geol. Mag. 108, p. 27-42.
- Westjohn, D.B., 1978, Finite strain in the Precambrian Kona Formation, Marquette County, Michigan. Unpublished M.S. Thesis. Michigan State University, E. Lansing, Michigan.

FIJI: THE RISE AND FALL OF AN ISLAND ARC -- A MODERN ANALOGUE TO PROTEROZOIC PLATE TECTONICS IN THE LAKE SUPERIOR REGION?

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Our understanding of Precambrian processes and events (including, for example, the evolution of Proterozoic terranes in the Lake Superior region) is commonly limited by the fragmentary nature of the data upon which our conclusions and our models are necessarily based. Not only must we contend with the selective removal of much of the geological record by erosion but, as has been increasingly well documented for the Phanerozoic evolution of western North America, tectonic disruption of formerly coherent terranes and juxtaposition of unrelated terranes is also common.

The scale and complexity of tectonomagmatic events which may have characterized the evolution of Precambrian terranes can perhaps be better appreciated by considering the evolution of younger, potential analogues of these older terranes. One such potential analogue is to be found in the magmatic and tectonic evolution of the Late Tertiary-to-Recent Fiji Archipelago in the southwestern Pacific.

The more than 300 Fijian islands are the subareal expression of a broad swell or plateau (the Fiji Platform) presently bounded by active magmatic arcs (the Tonga and Vanuatu arcs) and back-arc basins (the North and South Fiji Basins and the Lau Basin). Of the total land area (18233 km^2 , comparable to the northern third of the state of Wisconsin) more than 80% is contained in the two main islands of Viti Levu and Vanua Levu. A wide variety of igneous, metamorphic and sedimentary rock units, all of which bear witness to Fiji's evolution over the past 35-40 m.y., are found on these and the other islands of the group.

The basement of Viti Levu consists of low-K tholeiitic basalts and rare high-Mg (boninitic?) lavas. Calcalkaline basaltic-andesites and andesites which stratigraphically overlie these basalts have K-Ar ages of 8-9 m.y.b.p. and characterize the second stage of Fiji's evolution as an intra-oceanic magmatic arc. Beginning 5 1/2 to 6 million years ago high-potassium (shoshonitic) basalts were erupted across northern Viti Levu and from smaller volcanic centers to the east and southeast. Geochemical criteria (e.g., moderate to high enrichment of large ion lithophile elements such as K, Rb, Ba and light rare earth elements; low concentrations of high field strength cations such as Ti and Nb; and high Ba/La, Rb/Zr and La/Nb ratios) support the conclusion that these three volcanic stages were expressions of convergent plate boundary (subduction-related) magmatism. More recently, high-Ti alkali olivine basalts similar in chemistry to Hawaiian and other oceanic (intraplate) basalts have erupted from a dozen or so centers in the east-central part of the archipelago and witness a significant change in the tectonomagmatic environment.

Other significant episodes of volcanism include the Late Miocene eruption of high silica, low potassium rhyolites in northeastern Vanua Levu and continued calcalkaline volcanism (basaltic andesites and andesites) until about 3-4 m.y. ago on this same island.

Greenschist facies (burial?) metamorphism affected much of the low-K tholeiitic lavas on the island of Viti Levu and is, in part, spatially associated with an arcuate belt of 8-10 m.y. old trondjemitic plutons found in the southern part of the island. Last, but not least, sedimentary rocks are well represented on and around the islands by volcaniclastic grits, shales and marls as well as extensive carbonate barrier reef complexes of Miocene-to-Recent age.

Tectonic events which have attended (if not controlled) Fiji's magmatic evolution include fragmentation, translation and differential rotation of segments of the Vanuatu-Fiji-Tonga magmatic arc; in particular, late Miocene to middle Pliocene counterclockwise rotation of the Fiji platform and eastward migration of the Pacific-Australian plate boundary have isolated Fiji behind marginal basins floored by MORB-like basalts.

What might be the consequences of future tectonic events, perhaps ones associated with the ultimate closing of the Pacific Basin, upon the region? Perhaps most significant might be the consolidation of the various tectonostratigraphic units on and around the Fiji Platform into a coherent whole (a "terrane") -- the variety and complexity of the juxtaposed rock units in this terrane possibly mirroring the variety and complexity of the Lake Superior Proterozoic terranes (inferred to have been formed through a similar series of events characteristic of convergent plate boundaries).

The geology and petrology of the Garnet-Coloma
area, Garnet Range, Montana

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The Garnet-Coloma area lies approximately 30 miles east of Missoula, Montana in the Garnet Range. Exposures of Precambrian quartzites and Paleozoic sedimentary rocks have been intruded by a Cretaceous granitic stock (the Garnet stock). Numerous volcanic rocks of varied compositions are found to intrude the peripheral meta-sediments; a few have also been found to intrude the Garnet stock. The objectives of the study were two fold: 1) conduct a detailed geologic survey of the Garnet-Coloma area, and, 2) conduct petrographic and geochemical studies of rocks within the area.

Forty-three samples (24 plutonic and 19 volcanic) were analysed for major and minor elements (Si, Al, Fe, Mg, Ca, Na, K, Ti, Mn, P) by whole rock x-ray fluorescence. The analyses were used to determine: 1) if the Garnet stock was formed by a single or multiple intrusion, and 2) if the volcanic and plutonic rocks are genetically related to one another. These data will be used with the geologic mapping to examine possible tectonic implications of the Garnet stock's emplacement within the region.

Samples were collected and analysed along two traverses through the Garnet stock. Results for the W-E traverse are illustrated in the A-F-M diagram of figure 1. Samples have been renumbered to indicate their sequential location as one progresses eastward from the western meta-sediment - Garnet stock contact (1 - nearest the contact, 14 - furthest east). Two trends are noted in the W-E traverse. Similar trends have also been noted in the other traverse. Considering both the geochemistry and Garnet stock outcrop pattern, the author speculates that trend 1 corresponds to the first intrusive pulse and trend 2 corresponds to a later pulse. Normative oxide vs. SiO_2 diagrams (Harker diagrams) indicate that K_2O vs. SiO_2 is the most sensitive and may be used as a predictor to distinguish between the intrusive pulses. Petrographic examination of the respective trend samples show no significant differences.

In regards to the question: Are the volcanic and plutonic rocks genetically related? Comparisons of their geochemistry are inconclusive in proving or disproving comagmicity.

Ruppel et al. (1981) reported a K-Ar date for the Garnet stock at 82.4 ± 1 m.y. (hornblende) and 79.1 ± 7 m.y. (biotite). This indicates that the Garnet stock was emplaced during the same time span as the Boulder and Idaho batholiths. A plot of the Garnet stock and Garnet-Coloma volcanic samples' geochemistry on a ternary $\text{K}_2\text{O}-\text{Na}_2\text{O}-\text{CaO}$ diagram (figure 2) shows that nearly all the Garnet stock points lie in the overlap zone among Tilling's main and sodic series of the Boulder batholith, as well as Hyndman's Idaho batholith region. This high correspondence seems to imply a similar genesis for those intrusives,

EVENT	AGE
Intrusion of Wolf River Batholith and local hornblende hornfels metamorphism.	1500 Ma
Intrusion of Hines Quartz diorite.	?
Metamorphism (upper greenschist facies ?) and development of an S ₂ foliation.	1835 Ma
-----Baldwin Conglomerate -----	
Intrusion of mafic dikes.	?
Metamorphism to amphibolite facies, intrusion of Macauley gneiss border zone and development of S ₁ foliation.	?
Deposition of Waupee Volcanics and associated sedimentary rocks.	?
Intrusion of mafic dikes.	
Macauley Gneiss	?

Table 1 - Tentative geologic history for the Mountain area.

References Cited

Lahr, M. M., 1972, Precambrian geology of a greenstone belt in Oconto County, Wisconsin and geochemistry of the Waupee volcanics [M.S.thesis]: Madison, University of Wisconsin, 62 p.

possibly due to forming in the same environment or having a similar magma source. The Garnet-Coloma volcanic points as shown in figure 2 exhibit a much larger dispersion than the Garnet stock points. The volcanic points lie within the general region defined by the Boulder and Idaho batholiths, suggesting a similar magma source. This similarity is noted even though the volcanics are much younger (48-44 m.y.).

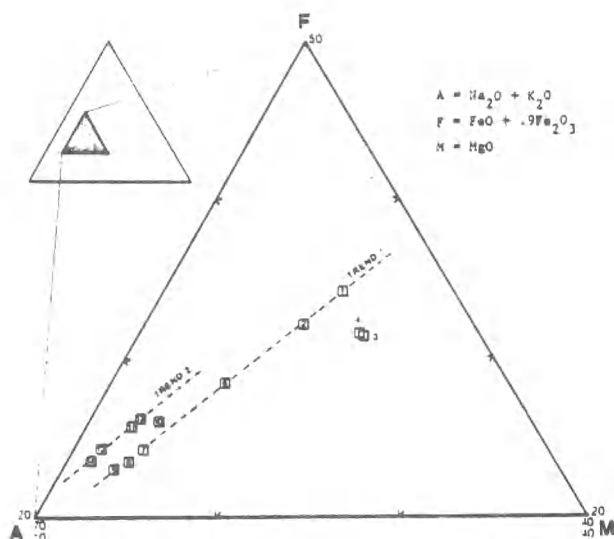


Figure 1. A-F-M plot of W-E traverse progressing eastward from the western meta-sediment - Garnet stock contact (1 - nearest contact, 14 - furthest east). Note the two trends.

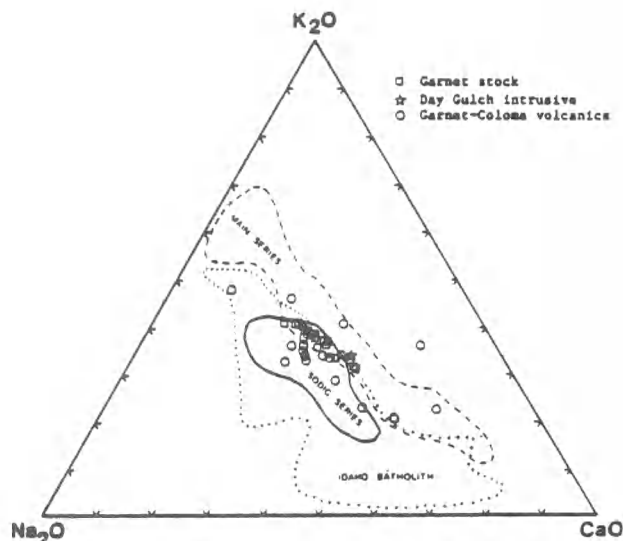


Figure 2. Ternary Na_2O - K_2O - CaO diagram showing fields for the Boulder batholith (Tilling, 1973) and the Idaho batholith (Hyndman, 1982) in relationship to analyses from the Garnet - Coloma area.

REFERENCES CITED

- Hyndman, D. W., A. J. Silverman, R. Ehinger, W. R. Benoit, and R. Wold. 1982. The Philipsburg batholith, western Montana - mineralogy, petrology, internal variation and evolution. Montana Bureau of Mines and Geology Memoir 49.
- Ruppel, E. T., C. A. Wallace, R. G. Schmidt, and D. A. Lopez. 1981. Preliminary interpretation of the thrust belt in southwest and west-central Montana and east-central Idaho. Pages 139-159. In T. Tucker (ed.) Montana Geological Society 1981 Field Conference and Symposium Guidebook to southwest Montana. Montana Geological Society.
- Tilling, R. T. 1973. Boulder batholith, Montana: A product of two contemporaneous but chemically distinct magma series. Geological Society of America, Bulletin, v. 84, p. 3879-3900.

DOES THE LAYERED MAFIC/ULTRAMAFIC
BODY NEAR MATLOCK, IOWA REPRESENT
AN OPHIOLITE OR CONTINENTAL INTRUSION?

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A layered mafic to ultramafic igneous body occurs in the subsurface in northwestern Iowa near the town of Matlock. Core samples of this body show that the complex is composed of olivine and pyroxene cumulates, gabbros, and anorthositic rocks. Some of the cumulate layers contain significant amounts of chromite. The body has been rotated such that the boundaries between the layers are very steep; no tectonic fabric is evident in thin sections, however. The position of this body near the postulated boundary between the Superior Province of Archean age and the extension of the Proterozoic Penokean terrane has led R. Anderson of the Iowa Geological Survey to speculate that the Matlock complex may represent an ophiolite which was implaced along a suture zone during the accretion of the Proterozoic rocks to the Archean craton (oral communication, 1984). We are conducting a geochemical study of this complex in an attempt to determine if these rocks have ophiolitic affinities (i.e., were formed originally in an oceanic or back-arc setting) or if they represent a layered continental intrusion. Data gathered during this study include major element concentrations, determined by XRF, and trace element abundances, determined by INAA.

The original igneous textures are still evident in the Matlock rocks, but their geochemistry has been significantly altered by later solutions. Rocks with greater concentrations of MgO are most severely altered and LOI subsequently correlates positively with MgO and negatively with SiO₂. LOI ranges from 2.23 to 17.7 weight percent and usually consists largely of H₂O with lesser CO₂. However, one rock contains 6.92 % CO₂ and 2.8 % H₂O. LOI also correlates positively with the elements Co and Cr which are concentrated in rocks with high MgO.

The trace elements can be divided into those which have remained immobile during the later alteration and those which have been altered. The immobile elements consist of the REE, Cs, Rb, Hf, Ta and Th. Ba and U have become enriched relative to the other elements in interelemental plots normalized to primordial mantle.

Plots of the immobile elements and their ratios appear to indicate that Matlock rocks have continental affinities and are most similar to continental tholeiites. Chondrite normalized REE exhibit flat to LREE/HREE enriched patterns with 1X chondrite abundance. La/Ta, Th/Ta and Th/Hf values are most similar to continental tholeiites. These data plus the lack of any discernible tectonic fabric support the interpretation of this body as being a layered continental intrusion.

GEOPHYSICAL AND REMOTE-SENSING CHARACTERISTICS OF THE COLORADO-WYOMING KIMBERLITE OCCURRENCES

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Hypervisible data collected from orbital, in situ, and multi-temporal perspectives between 1976 and 1981 provide the basis for identifying several new and potentially diagnostic properties that are characteristic of the Devonian kimberlites that intrude Precambrian crystalline rocks in northcentral Colorado and southeast Wyoming. The kimberlite occurrences, which total more than 100, are exposed, and thus provide an excellent opportunity to monitor differences between Paleozoic ultramafic intrusives and their older felsic host, without the complications of recent glacial cover.

Small-scale (1:1,000,000) black and white Landsat infrared images and complementary geophysical maps of the region exhibit a transverse or cross-cutting textural signature which is thought to reflect the intersection of deep-seated zones of structural weakness that were preferentially exploited by ascending kimberlite melts. Similar signatures are evident in evaluations of comparable data from kimberlite provinces in Siberia and East Africa.

In situ ground-based geophysical traverses conducted over eight Colorado-Wyoming kimberlite locations document the occurrence of two different types of kimberlite: (1) a deeply weathered variety characterized by greater conductivity, lower density, and a somewhat similar range of magnetic values with respect to the granite host, and (2) a relatively unweathered variety characterized by similar conductivity, higher density, and substantially higher magnetic readings with respect to the granite host (see Fig. 1). The diameters of these occurrences range from 3 m (10 ft) to 120 m (400 ft), the larger features tending to be deeply weathered and the smaller features relatively unweathered. In accordance with the upward-flaring "pilsner-glass model" postulated to describe the emplacement-habit of gas-charged vent features rising explosively from a feeder dike at depth, the two types of kimberlite are believed to correspond respectively to a shallower diatreme facies and a deeper hypabyssal facies, which have been exposed by differing depths of erosion since the Devonian time of emplacement.

In situ multivariate trends in soil moisture, vegetation reflectance, and soil temperature data collected twice-monthly from late May to November at a deeply weathered kimberlite diatreme (Schaffer 15) show significant variations between this lithology and the surrounding granite. Soil moisture readings taken to a depth of 2 m (6 ft) show that the moisture content of the kimberlite soil is persistently 3-6 times greater than that of the granite soil throughout the 6-month monitoring period, although both lithologies undergo a progressive dessication from June to November. The contrast is believed to reflect the greater moisture-retaining capacity of the thicker, montmorillonite-rich weathered zone over the kimberlite in a semi-arid environment, and probably contributes substantively to the electrical conductivity difference noted above. In terms of geobotanical variations, the infrared(0.76-0.90 μ m)/visible(0.63-0.69 μ m) reflectance ratio, an index of surface

biomass obtained with a handheld radiometer, was observed to be consistently higher for the kimberlite grass cover vs the granite grass cover from May through September. Post-September values are similar for both grass covers because of autumnal senescence which results from diminished precipitation and the onset of freezing temperatures. Soil temperature profiles recorded to a depth of 2 m (6 ft) in kimberlite and granite soils exhibit characteristic seasonal slopes (positive in summer, negative in winter) but no noticeable difference in thermal properties on any given date, which may reflect in part the practice of collecting temperature data in the afternoon hours when insolation effects are at a maximum. However, daily temperature variations reflect slight differences between the kimberlite and granite soils (e.g. deeply weathered kimberlite at the Schaffer 15 diatreme was 1°C cooler than the adjacent granite during the nighttime hours of a diurnal cycle monitored in September).

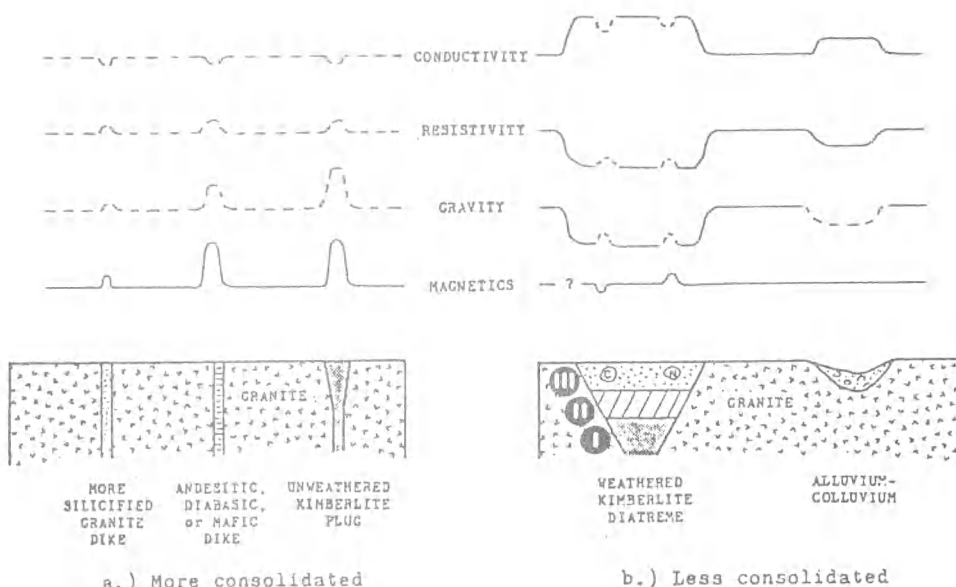
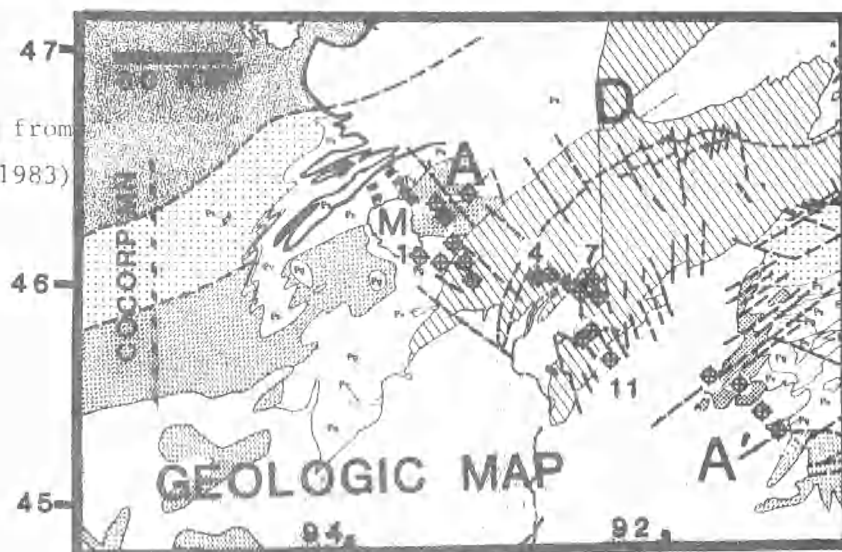


Figure 1. Schematic cross-sectional depiction of a.) more consolidated and b.) less consolidated features and their characteristic geophysical signatures with respect to the granitic country rock of Colorado and Wyoming. Weathered kimberlite diatreme consists of layer I (massive, hypabyssal kimberlite) layer II (highly conductive, deeply weathered kimberlite), and layer III (less conductive, shallow weathered layer containing xenoliths of carbonate (C) and upper mantle nodules (N)). Geophysical signatures dashed where based on theoretical considerations rather than actual measurements. Magnetic signatures are based on east-west traverses.

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(Basemap from
Morey, 1983)



Profile: sedimentary rocks of Paleozoic and Mesozoic strata overlies

 Karstic and Superkarst, unroofed
 Active and extinct volcanic rocks, unroofed
 Red - Paleozoic superkarst tanks, unroofed; mainly igneous
 rocks by granite

 Igneous rocks, unroofed

 Tertiary rocks of the Andean belt and volcanic and/or igneous rocks
 in the range, major volcanic ranges, active and extinct
 Tertiary volcanic, major volcanic ranges, active and extinct volcanic ranges
 by igneous activity, volcanic ranges, active and extinct volcanic ranges
 volcanic ranges

 Tertiary volcanic ranges, active and extinct volcanic ranges
 volcanic ranges and the granite ranges

 Tertiary volcanic ranges, active and extinct volcanic ranges
 volcanic ranges, active and extinct volcanic ranges

 Tertiary volcanic ranges, active and extinct volcanic ranges
 volcanic ranges, active and extinct volcanic ranges

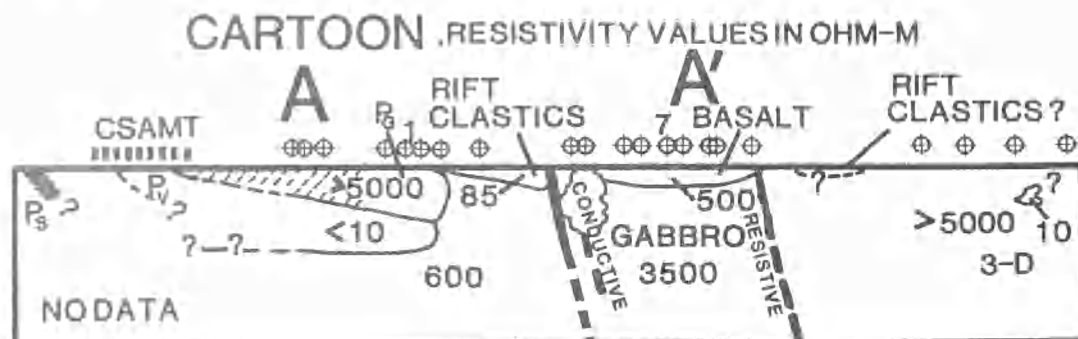
 Tertiary volcanic ranges, active and extinct volcanic ranges
 volcanic ranges, active and extinct volcanic ranges

 Tertiary volcanic ranges, active and extinct volcanic ranges
 volcanic ranges, active and extinct volcanic ranges


BOLD SYMBOLS--SEE TEXT

Another MT study used high frequency controlled source signal (CSAMT) designed to explore the resistivity structure of the upper few km. This study (EM Surveys, 1985) was located along two lines N of Mille Lacs (heavy dashed lines). The more easterly line crosses the extreme northern edge of the McGrath Gneiss and then the Glen Township Formation (Pv).

One and 2-dimensional modeling of MT data is now underway and tentative results are summarized by the cartoon (no vertical scale intended but the



bottom is at about 20 km). Key features include:

1. In the crust west of the rift a wedge shaped, conductive body has been detected beneath mapped McGrath Gneiss and Isle Granite, shallowing progressively to the NW. The presense of a dissimilar lithology beneath these crystalline rocks is consistent with the undulatory nature of the gravity and magnetic data in the region (V. Chandler, pers. comm.). The overlying crystalline rocks are resistive (at least 5000 ohm-m) and these are at least several km thick at Site 1. The conductive rocks below them are everywhere less than about 20 ohm-m and at Site 1 appear about 10 km thick.

The dipping conductive body may or may not intersect the surface and more MT sites are required to explore the broad regional resistivity structure bearing on this question. However extrapolation of the MT data ($\oplus$'s) suggests the conductive body would potentially intersect the surface in the general vicinity of the Animikie basin. The CSAMT data over the northern edge of the McGrath Gneiss conform with this: a) the truncation of the gneiss occurs along a southerly dipping boundary, and b) parts of the Pv unit show a similar inclination.

Although the body is clearly beneath Site 1, detection beneath sites just to the east toward the SC, is equivocal. Across on the eastern rift flank in Wisconsin sites are dominated by complex resistivity behavior which is very difficult to model. The suggestion though is that a pervasive, thick conductive body analogous to that on the western rift flank is absent here. Thus the gross resistivity structures on either side of the rift appear dissimilar.

2. Over the central portions of the SC a resistive zone is indicated, generally below a few km, which is presumably the intrusive gabbroic portion of the rift. There is insufficient resistivity contrast between these gabbros and adjacent crustal material to clearly resolve deeper portions of the rift. Judging from resistivity responses, the axis of the igneous rocks comprising the SC is located at Site 7. This is at the structural axis of the rift as judged by previous geophysics and from the synclinal geometry of rift clastics deposited nearby. Pronounced differences in resistivity are observed at the east and west margins of the SC--conductive to the west and resistive to the east. Therefore the overall rift resistivity structure is broadly asymmetric.

In conclusion, both the rift and surrounding crust are asymmetrical -- resistive to the east. The conductive body on the western rift flank needs further investigation but may extend from the Animikie basin to proximity with the rift margin.

REFERENCES:

- ElectroMagnetic Surveys, Inc., 1985, CSAMT Survey, Aitkin Co., Minn., Rep. 8417, v.1 (for Minn. Dept. of Nat. Res., Hibbing, MN.)
Morey, G.B., 1983, Animikie Basin, Lake Superior Region, U.S.A., Chapter 2, in Iron Formation: Facts and Problems, Trendall and Morris (eds.), pp. 13-67, Elseviers Sci. Publ., Amsterdam

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