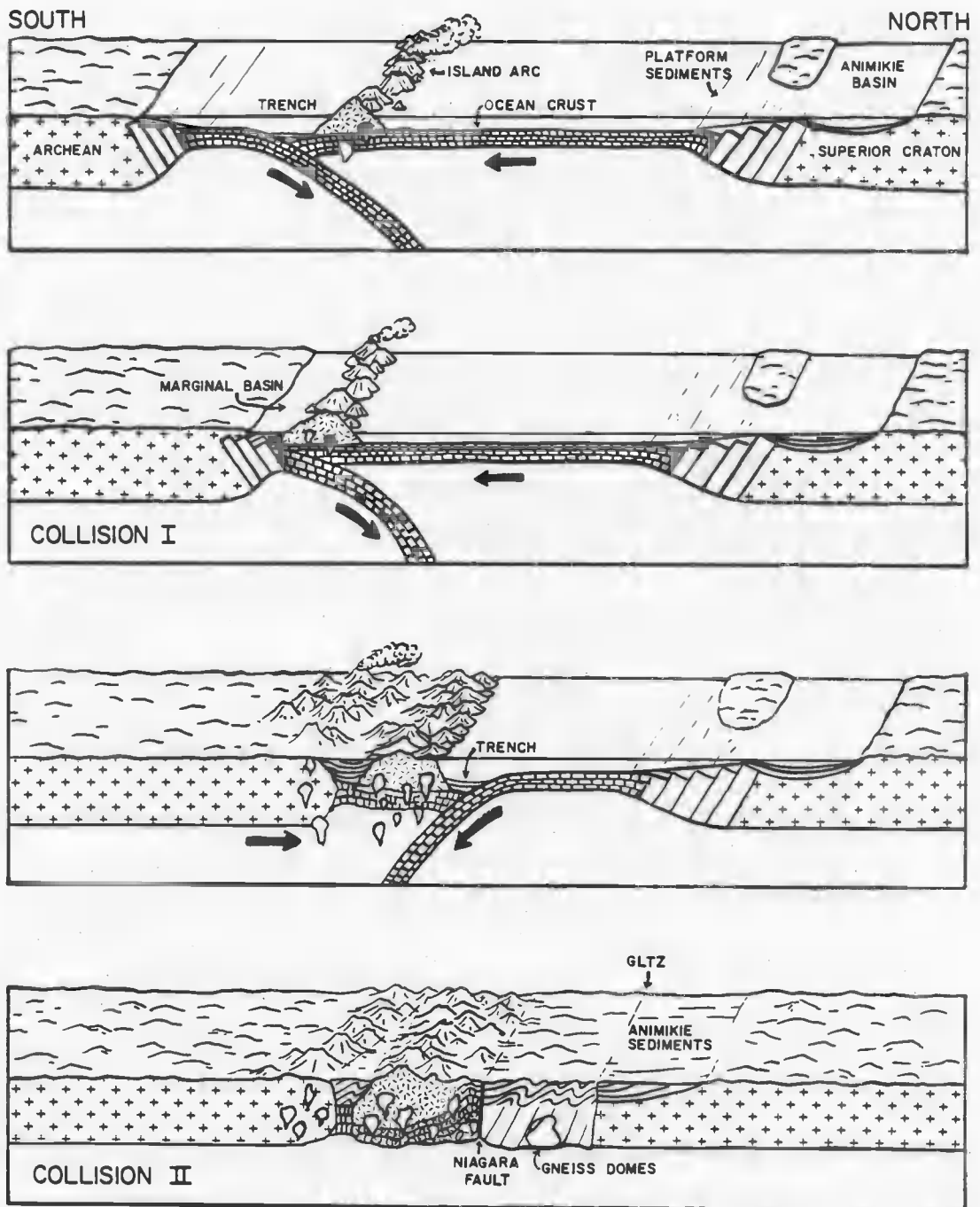




THIRTIETH ANNUAL INSTITUTE ON LAKE SUPERIOR GEOLOGY

ABSTRACTS



Wausau, Wisconsin
April 24-28, 1984

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, MI
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.

Award Guidelines

SAM GOLDICH MEDAL

Preamble

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

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

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

Award Guidelines

- 1) The medal shall be awarded annually by the Board of Directors, I.L.S.G., to a geologist whose name is associated with a substantial sustained interest in, or a major contribution to, the geology of the Lake Superior Region.
- 2) The Board of Directors, I.L.S.G. shall appoint the Nominating Committee. Their annual nominee will be voted on at the annual business meeting. The initial appointment will be of three members, one to serve for three years, one for two, and one for one year, the member with the briefest incumbency to be chairman. After the first year the Board of Directors shall appoint at each spring meeting one new member who will serve for three years. In the third year this member shall be the chairman. The Committee membership should reflect the main fields of interest and geographic distribution of I.L.S.G. membership.
- 3) The Goldich Medal Nominating Committee shall select the medalist and will make its recommendation to the Board of Directors by November 1 of that year.
- 4) The Board of Directors normally will accept the nominee of the Committee, will inform the medalist immediately, and will have one medal engraved appropriately for presentation at the May meeting.
- 5) It is recommended that the Institute set aside annually from whatever sources, such funds as will be required to support the continuing costs of this award.

April 4, 1981

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

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)

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.

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GENERAL INFORMATION

30th ANNUAL
INSTITUTE ON LAKE SUPERIOR GEOLOGY

Held at
HOLIDAY INN
Wausau, Wisconsin, 54901
April 26, 27, 1984

sponsored by
The Geology Department
The University of Wisconsin-Oshkosh
Program Chairman and Editor
Gene L. LaBerge

INSTITUTE BOARD OF DIRECTORS

- G. L. LaBerge, Department of Geology, University of Wisconsin-Oshkosh,
Oshkosh, Wisconsin, 54901 (1984)
- T. J. Bornhorst, Department of Geology and Geological Engineering,
Michigan Technological University, Houghton, Michigan, 49931 (1983)
- D. L. Southwick, Minnesota Geological Survey, 2642 University Avenue,
St. Paul, Minnesota, 55114 (1982)
- F. W. Cambray, Department of Geology, Michigan State University, East
Lansing, Michigan, 48824 (1981)
- P. E. Myers, Department of Geology, University of Wisconsin-Eau Claire,
Eau Claire, Wisconsin, 54701 (1980)
- J. Kalliouloski, Department of Geology and Geological Engineering, Michigan
Technological University, Houghton, Michigan, 49931 (Secretary-Treasurer)

SALES

Copies of the Abstracts and Field Trip Guidebooks may be purchased from Gene L. LaBerge, Geology Department, University of Wisconsin-Oshkosh, Oshkosh, WI, 54901. Abstracts = \$6.00; Guidebooks I, II and III = \$5.00 each. Make checks payable to: Institute on Lake Superior Geology.

LOCAL COMMITTEE

Conference Chairman

Gene L. LaBerge

Field Trips

P. K. Sims, U.S. Geological Survey, Federal Center, Denver,
Colorado, 80225

Klaus J. Schulz, U.S. Geological Survey, National Center,
Reston, Virginia, 22092

Zell E. Peterman, U.S. Geological Survey, Federal Center,
Denver, Colorado, 80225

Paul E. Myers, Geology Department, University of Wisconsin-
Eau Claire, Eau Claire, Wisconsin, 54701

W. L. Ueng, D. K. Larue, R. L. Sedlock, D. A. Kasper,
Department of Geology, Stanford University, Stanford,
California, 94305

Registration

Sally LaBerge, Geology Department, University of Wisconsin-
Oshkosh, Oshkosh, Wisconsin, 54901

Best Student Paper Committee

Paul E. Myers, Geology Department, University of Wisconsin-
Eau Claire, Eau Claire, Wisconsin, 54701

Val W. Chandler, Minnesota Geological Survey, 2642 University
Avenue, St. Paul, Minnesota, 55114

Eugene C. Perry, Geology Department, Northern Illinois University,
DeKalb, Illinois, 61455

GOLDICH MEDAL COMMITTEE

R. L. Buchheit, Meridian Land and Mineral Company, Box 566,
Hibbing, Minnesota, 55746

W. F. Cannon, U.S. Geological Survey, MS 954, National Center,
Reston, Virginia, 22092

M. F. Kehlenbeck, Department of Geology, Lakehead University,
Thunder Bay, Ontario

SESSION CHAIRMEN

Robert L. Bauer, Department of Geology, University of Missouri,
Columbia, Missouri

Theodore J. Bornhorst, Department of Geology and Geological
Engineering, Michigan Technological University, Houghton,
Michigan

James I. Hoffman, Department of Geology, University of Wisconsin-
Oshkosh, Oshkosh, Wisconsin

Thomas R. Kalk, Homestake Mining Company, P. O. Box 10628,
Reno, Nevada

John S. Klasner, Department of Geology, Western Illinois
University, Macomb, Illinois

Gregory Mursky, Department of Geological Sciences, University
of Wisconsin-Milwaukee, Milwaukee, Wisconsin

Peter A. Nielsen, Department of Geology, University of Wisconsin-
Parkside, Kenosha, Wisconsin

Klaus J. Schulz, U. S. Geological Survey, National Center, MS 954,
Reston, Virginia

GOLDICH MEDAL RECIPIENT

Richard W. Ojakangas, Geology Department, University of
Minnesota-Duluth, Duluth, Minnesota

ANNUAL BANQUET SPEAKER

Dr. Charles Meyer, 380 Smith Road, Sedona, Arizona

ACKNOWLEDGEMENTS

Any conference of this type requires the cooperation of many individuals who are willing to give of their time. As general chairman I sincerely appreciate the widespread cooperation I have had by the many people I have asked to help make the conference a success. A special thanks goes to my colleagues at UW-Oshkosh, especially our secretary Sara Margis for the typing and many other functions she has performed. I couldn't have done it without you all.

REPORT OF THE CHAIRMAN

29th INSTITUTE ON LAKE SUPERIOR GEOLOGY

1983

The 29th Institute on Lake Superior Geology was held May 11-14, 1983 at Michigan Technological University in Houghton, Michigan. The meeting was sponsored by the Michigan Tech Department of Geology and Geological Engineering in cooperation with the Division of Education and Public Services. Registrants numbered 173, including 119 professional geologists and 54 students. The program included a pre-meeting one day field trip to provide an overview of the geology of the Keweenaw Peninsula, Michigan, a post-meeting one day field trip to the Ropes and Michigan gold mines near Ishpeming, Michigan and four half-day sessions of technical papers. About 70 persons participated in the pre-meeting trip, about 60 participated in the post-meeting trip, and 31 papers were selected for oral presentation at the technical sessions. The proceedings of the 29th Institute were published in two volumes. Volume I included the accepted abstracts and the field trip road log to the Ropes gold mine. Volume II was a geologic field guide for the Keweenaw Peninsula.

The Annual Banquet was held on May 12, 1983 and was attended by around 100 people. Burt Boyum was awarded the Institute's Goldich Medal. Unfortunately Burt was out of the country and Roy Koski accepted the medal in his absence. Bob Reed was thanked by Ralph Marsden for his dedicated service for many years as the Institute's Secretary-Treasurer; this was Bob's last meeting in that role. The banquet address was given by Dr. Stephen E. Kesler, University of Michigan, who compared and contrasted precious metal deposits of Tertiary age in the Caribbean to those of Archean age in Canada. His stimulating talk provided a fine touch to a meal of prime rib and trimmings.

Dean Rossell, graduate student at Michigan Technological University, received a cash award of \$200 for presenting the best paper by a student. His paper was entitled "Alteration of the Deer Lake Peridotite in the vicinity of the Ropes gold mine, Marquette County, Michigan". Dean was co-leader of the field trip to the Ropes gold mine. The Best Student Paper Committee recognized all students for their good presentations and found it difficult to pick a winner. Students play an important role in the Institute and it is hoped that the quality of their papers continues to improve.

The Board of Directors of the Institute met on May 12, 1983. Present at the meeting were: T.J. Bornhorst (Chairman), D.L. Southwick, P.E. Myers, M.F. Kehlenbeck, R.C. Reed (Secretary-Treasurer) and G.L. LaBerge (incoming 1984 Chairman). The Board took the following action:

1. Accepted with thanks the continued offer of the Minnesota Geological Survey to maintain and update the mailing list of the I.L.S.G.
2. Accepted with enthusiasm the offer of the Ontario Geological Survey to host the 31st I.L.S.G. at Kenora, Ontario in 1985.
3. Agreed that financing for the 1985 meeting in Kenora should go through the Canadian I.L.S.G. account, M.M. Kehlenbeck, custodian.

4. Moved that the summary report of the Chairman from the previous year, the Institute's Constitution, the Goldich Award selection rules, a list of previous Institutes and location, and the address of the Secretary-Treasurer (where previous Proceedings Volumes can be obtained) be included in the Proceedings Volume.
5. Instructed that the Chairman of each Institute should budget on the basis of pre-registration with the goal of breaking even. Excess money can be accumulated without I.R.S. penalty.
6. Moved that transportation to and from the meeting will be paid for the Goldich Award recipient, if needed. This cost should be included in the budget for each meeting.
7. Moved that the Chairman of each Institute decide what expenses are reasonable for field trip presentation.
8. Decided to discontinue the I.L.S.G. Bibliography. It was not used enough to warrant the amount of effort involved in updating.
9. Discussed the publication of a special volume of papers as requested by Dr. Larue (via Dr. LaBerge). Tabled this issue until the 50th Institute.
10. Noted that papers extraneous to the field trip should not be published in the Proceedings Volume. The Board of Directors' desire is to keep the Proceedings Volume uncluttered.
11. Appointed M.F. Kehlenbeck (representing academia) to a 3-year term on the Goldich Medal Selection Committee. Dick Buchheit is the 1984 Chairman of this Committee. The Board instructs the Committee to deliver the name of the nominee to the Chairman by no later than January 1 of each year. This deadline is necessary for budget purposes.
12. Nominated G. Morey, J. Kalliokoski, and Paul Myers for the Institute's Secretary-Treasurer and directed the Chairman to accept other nominations from the membership. The new Secretary-Treasurer will be elected by closed ballot vote of the members present.
13. Instructed the new Secretary-Treasurer to hold U.S. I.L.S.G. funds in an interest-bearing account that pays the maximum interest rate obtainable while maintaining high liquidity.
14. Instructed that the Secretary-Treasurer will sell and hold Proceedings Volumes from previous meetings. The extra unsold copies of the Proceedings Volumes will be given to the Secretary-Treasurer at the conclusion of each meeting. The extra copies will be kept until the next year's meeting and after that can be discarded. Copies of previous volumes can be obtained from the Secretary-Treasurer at the cost of xerox, shipping and handling. The address of the Secretary-Treasurer will be listed on the back of the Proceedings Volume so that orders can be directed to that office.
15. Instructed that the Secretary-Treasurer print I.L.S.G. stationary and make it available to the Chairman of each meeting.

16. Moved that the Institute not be formalized beyond that stated in the Constitution.
17. Discussed and suggested that group travel arrangements for the 1985 meeting in Kenora, Ontario be investigated. Ideas for such transportation included a bus from Duluth northward, perhaps arranged by a UMD faculty liaison, or possibly a chartered plane flight.

The election for a new Secretary-Treasurer was held on May 13, 1983.

J. Kalliokoski, Department of Geology and Geological Engineering, Michigan Technological University, was elected to the post. I'm sure that the Institute will benefit from Joe's forthcoming effort as Secretary-Treasurer. Financially the 29th I.L.S.G. concluded with a small deficit. There is about \$2,900 in the Institute's U.S. account and about \$3,300 in the Canadian account.

The task of organizing the 29th I.L.S.G. was an enlightening experience in more ways than one. I'm glad my responsibilities are ending and pass on the job of Chairman to Gene LaBerge, University of Wisconsin, Oshkosh.

Respectfully submitted,



Theodore J. Bornhorst
Chairman 29th I.L.S.G.
September 21, 1983
Houghton, Michigan

CALENDAR OF EVENTS

AND

PROGRAM

MONDAY, APRIL 23, 1984

6:00 p.m. - 9:00 p.m. DINNER AND ORIENTATION FOR PARTICIPANTS IN
FIELD TRIP I. - Four Seasons Club, Beecher,
Wisconsin.

TUESDAY, APRIL 24, 1984

8:00 a.m. - 6:00 p.m. FIELD TRIP I: GEOLOGY OF THE EARLY PROTEROZOIC
ROCKS IN NORTHEASTERN WISCONSIN--Day 1, Dunbar
Gneiss--Granitoid Dome--P.K. Sims, K.J. Schulz,
and Z.E. Peterman.

WEDNESDAY, APRIL 25, 1984

8:00 a.m. - 4:00 p.m. FIELD TRIP I: GEOLOGY OF THE EARLY PROTEROZOIC
ROCKS IN NORTHEASTERN WISCONSIN--Day 2,
The northeastern Wisconsin volcanic rocks--
K.J. Schulz, P.K. Sims, and Z.E. Peterman.

7:00 p.m. - 10:00 p.m. REGISTRATION, LOBBY, HOLIDAY INN, WAUSAU

7:00 p.m. - 10:00 p.m. SMOKER AND CASH BAR, HOLIDAY INN, WAUSAU

7:00 p.m. - 10:00 p.m. POSTER PRESENTATIONS

Bruce A. Brown and J.K. Greenberg--EARLY PROTEROZOIC
STRUCTURES OF NORTHEASTERN WISCONSIN AS CONSTRAINTS
ON PENOKEAN TECTONIC MODELS

Al U. Falster--MINERALOGY OF PEGMATITES IN THE WAUSAU
PLUTON, MARATHON COUNTY, WISCONSIN

Elizabeth R. King, John H. Karl, John S. Klasner, and
William J. Jones--COMPOSITE MAGNETIC MAP OF WISCONSIN
PRECAMBRIAN FROM NEW COMPILATION OF DIGITAL
AEROMAGNETIC DATA

Dennis Mackovjak and Joseph Mancuso--GEOLOGY OF THE LONE
MOUNTAIN GOLD PROSPECT, NORTHEAST NEVADA

M.G. Mudrey, Jr. and J. Kalliokoski--METALLOGENY OF THE
LAKE SUPERIOR PRECAMBRIAN

P.A. Nielsen--MDB - A METAMORPHIC MINERAL ASSEMBLAGE
DATABASE FOR THE PRECAMBRIAN OF THE LAKE SUPERIOR
DISTRICT

WEDNESDAY, APRIL 25, 1984 - continued

P.A. Nielsen--METAMORPHIC CONDITIONS AND EVOLUTION
OF A SUPRACRUSTAL SEQUENCE INTRUDED BY THE
DUNBAR GNEISS, FLORENCE AND MARINETTE COUNTIES,
NORTHEASTERN WISCONSIN

E.C. Perry, Jr., J. Feng and J. Hemzacek--PRECAMBRIAN
EVAPORITES: PRESERVATION OF SULFATE IN QUARTZ
PSEUDOMORPHS AFTER GYPSUM

*W.L. Petro--CRYSTALLIZATION HISTORIES OF EARLY PROTEROZOIC
PLUTONS FROM NORTHERN WISCONSIN

*Christopher A. Scholz--LATE AND POST-GLACIAL LACUSTRINE
SEDIMENT DISTRIBUTION IN WESTERN LAKE SUPERIOR
FROM SEISMIC REFLECTION PROFILES

Michael J. Schwartz and P.A. Nielsen--REGIONAL CONTROLS ON
ARCHEAN METALLOGENY IN THE UPPER PENINSULA OF MICHIGAN

*Kevin Sikkila--PETROGRAPHIC AND GEOCHEMICAL STUDY OF THE
MOUNT BOHEMIA STOCK, PORTAGE LAKE VOLCANICS,
KEWEENAW PENINSULA, MICHIGAN

W.R. Van Schmus--RECENT CONTRIBUTIONS TO THE GEOCHRONOLOGY
OF THE PRECAMBRIAN OF WISCONSIN

NOTE: All Papers eligible for the Best Student Paper Award
are marked with an asterisk (*).

THURSDAY, APRIL 26, 1984

7:30 a.m. - 4:30 p.m.	REGISTRATION, LOBBY, HOLIDAY INN, WAUSAU
8:00 a.m. - 5:00 p.m.	POSTER PRESENTATIONS (Authors need not stay with posters)
8:00 a.m. - 11:50 a.m.	TECHNICAL SESSION I, John S. Klasner, Thomas R. Kalk, Co-chairmen
8:00 a.m.	WELCOME TO 30th I.L.S.G.--Gene L. LaBerge
8:10 a.m.	Warren C. Day--GEOLOGY OF THE RAINY LAKE AREA, NORTHERN MINNESOTA-REVISITED
8:30 a.m.	*Steven Osterberg--STRATIGRAPHY OF THE HEADWAY-COULEE MASSIVE SULPHIDE PROSPECT, NORTHERN ONAMAN LAKE AREA, NW ONTARIO
8:50 a.m.	<u>Peter J. Hudleston</u> and David L. Southwick--THE ROLE OF TRANSCURRENT SHEAR IN DEFORMATION OF THE ARCHEAN ROCKS OF THE VERMILLION DISTRICT, MINNESOTA

THURSDAY, APRIL 26, 1984 - continued

9:10 a.m. David P. Moecher and L.G. Medaris, Jr.--LATE
ARCHEAN METAMORPHIC CONDITIONS AT GRANITE
FALLS, MINNESOTA

9:30 a.m. Anthony Mariano and H.H. Woodard--POTASSIUM
METASOMATISM OF TRONDHJEMITE MIGMATITE
WALLROCK, VERMILION COMPLEX, NORTHERN
MINNESOTA

9:50 a.m. COFFEE BREAK

10:10 a.m. R.L. Hackenberg and Gregory Mursky--MOBILIZATION
OF URANIUM AND THORIUM WITHIN THE REPUBLIC
METAMORPHIC NODE, NORTHERN MICHIGAN

10:30 a.m. Anthony W. Shepeck and T.J. Bornhorst--
CHARACTERIZATION OF THE ORE HOST ROCK AT
THE ROPES GOLD MINE, ISHPEMING, MICHIGAN

10:50 a.m. Thomas J. Kirsling, C.W. Montgomery, and E.C.
Perry Jr.--RB-SR AND OXYGEN ISOTOPE SYSTEMATICS
OF ARCHEAN GREY GNEISSES OF THE SOUTHWESTERN
BEARTOOTH MOUNTAINS

11:10 a.m. Karl E. Seifert--TRACE ELEMENT GEOCHEMISTRY OF
SOME LAKE SUPERIOR KEWEENAWAN BASIC LAYERED
INTRUSIONS

11:30 a.m. Patrick Ryan and Paul W. Weiblen--PT AND NI
ARSENIDE MINERALS IN THE DULUTH COMPLEX

11:50 a.m. LUNCH BREAK

ANNUAL MEETING, I.L.S.G. BOARD OF DIRECTORS

1:20 p.m. - 4:20 p.m. TECHNICAL SESSION II, Theodore J. Bornhorst,
James I. Hoffman, Co-chairmen

1:20 p.m. James B. Paces and Theodore J. Bornhorst--
ALTERATION, PARAGENESIS AND AGE ASSOCIATE
WITH NATIVE COPPER MINERALIZATION OF THE
KEARSARGE FLOW, KEWEENAW PENINSULA, MICHIGAN

1:40 p.m. S.A. Hauck and E.W. Kendall--COMPARISON OF MIDDLE
PROTEROZOIC IRON OXIDE RICH ORE DEPOSITS.
MID-CONTINENT, U.S.A., SOUTH AUSTRALIA, SWEDEN,
AND THE PEOPLES REPUBLIC OF CHINA

2:00 p.m. R.D. Powell--CLIMATIC INFERENCES OF IRON-FORMATION
FROM ASSOCIATED DIAMICTITE FACIES SEQUENCES,
GRIQUALAND WEST SUPERGROUP, SOUTH AFRICA

THURSDAY, APRIL 26, 1984 - continued

- 2:20 p.m. E. Schuessler and E.C. Perry, Jr.--METAMORPHISM
OF KURUMAN AND GRIQUATOWN IRON FORMATIONS AND
ASSOCIATED MAKGANYENE DIAMICTITE, CAPE PROVINCE,
SOUTH AFRICA: A STABLE ISOTOPE INVESTIGATION
- 2:40 p.m. COFFEE BREAK
- 3:00 p.m. *Erik G. Shaw--DIKES AS TECTONIC INDICATORS IN THE
EASTERN LAKE SUPERIOR REGION-STRUCTURAL AND
PALEOMAGNETIC CONSIDERATIONS
- 3:20 p.m. *Ted R. Repesky--MAGNETOTELLURIC PROFILE OF THE
JACOBSTOWN SANDSTONE
- 3:40 p.m. W.F. Kean, D. Mercer and E. Ramthun--PRELIMINARY
PALEOMAGNETIC RESULTS FROM THE BARABOO
QUARTZITE AND THE ASSOCIATED RHYOLITE AND
GRANITE INLIERS OF SOUTH CENTRAL WISCONSIN
- 4:00 p.m. L.G. Soroka and J. Josch--MORPHOLOGY, MICROSTRUCTURE
AND ACCRETION RATE OF RECENT ALGAL STROMATOLITES
FROM EAGLE LAKE, OTTERTAIL COUNTY, MINNESOTA
- 4:20 p.m. Richard A. Paull--LOCALIZED ACCUMULATIONS OF UPSIDE
DOWN TRILOBITE PARTS IN CAVITIES WITHIN A
SILURIAN REEF AT RACINE, WISCONSIN
- 6:00 p.m. SOCIAL HOUR--CASH BAR
- 7:00 p.m. ANNUAL BANQUET
- Announcement of 1985 Meeting in Kenora, Ontario
- Presentation of Goldich Award to R. W. Ojakangas
by S.S. Goldich
- Guest Speaker--Dr. Charles Meyer
- "THE ORE METALS IN EARTH HISTORY"

FRIDAY, APRIL 27, 1984

- 8:00 a.m. - 11:50 a.m. TECHNICAL SESSION III, Klaus J. Schulz and
Robert L. Bauer, Co-chairmen
- 8:00 a.m. P.K. Sims, Z.E. Peterman, and Klaus J. Schulz--
A PARTISAN REVIEW OF THE EARLY PROTEROZOIC
GEOLOGY OF WISCONSIN AND ADJACENT MICHIGAN
- 8:30 a.m. G.B. Morey and D.L. Southwick--EARLY PROTEROZOIC
GEOLOGY OF EAST-CENTRAL MINNESOTA-A REVIEW
AND REAPPRAISAL

FRIDAY, APRIL 27, 1984 - continued

8:50 a.m.	Grant M. Young--THE HURONIAN SUPERGROUP: AN EXAMPLE OF AN EARLY PROTEROZOIC PASSIVE MARGIN SEQUENCE
9:10 a.m.	<u>Gene L. LaBerge</u> , Klaus J. Schulz and Paul E. Myers--THE PLATE TECTONIC HISTORY OF NORTH CENTRAL WISCONSIN
9:40 a.m.	COFFEE BREAK
10:10 a.m.	Klaus J. Schulz--EARLY PROTEROZOIC PENOKEAN IGNEOUS ROCKS OF THE LAKE SUPERIOR REGION: GEOCHEMISTRY AND TECTONIC IMPLICATIONS
10:30 a.m.	*Warren Beck--ND AND SM ISOTOPIC STUDIES OF THE QUINNESEC AND HEMLOCK FORMATIONS IN NORTHEASTERN WISCONSIN AND ADJACENT MICHIGAN
10:50 a.m.	Timothy B. Holst--PENOKAN TECTONICS: CONSTRAINTS FROM STRUCTURAL GEOLOGY IN EAST-CENTRAL MINNESOTA
11:10 a.m.	*Richard C. Clark--MICROSTRUCTURES IN THE MULTIPLY DEFORMED SLATE OF THE THOMSON FORMATION, EAST-CENTRAL MINNESOTA
11:30 a.m.	<u>F.W. Cambray</u> , R.O. Meyer and G.A. Myers--BASEMENT COVER RELATIONS IN THE MARQUETTE AND REPUBLIC DISTRICTS, MICHIGAN
11:50 a.m. - 1:10 p.m.	LUNCH BREAK
1:10 p.m. - 4:30 p.m.	TECHNICAL SESSION IV, Peter A. Nielsen and Gregory Mursky, Co-chairmen
1:10 p.m.	W.L. Ueng, <u>D.K. Larue</u> and R.L. Sedlock--GEOLOGIC HISTORY AND PALINOSPASTIC RECONSTRUCTION OF THE EARLY PROTEROZOIC PENOKEAN COLLISION ZONE
1:30 p.m.	<u>John S. Klasner</u> and Dan Osterfeld--GRAVITY MODELS OF GNEISS DOMES AND A GRANITE PLUTON IN NORTHEASTERN WISCONSIN
1:50 p.m.	Richard W. Ojakangas--BASAL LOWER PROTEROZOIC GLACIOGENIC FORMATIONS, MARQUETTE RANGE SUPERGROUP, UPPER PENINSULA, MICHIGAN
2:10 p.m.	S.S. Goldich--PRECAMBRIAN GEOCHRONOLOGY OF MINNESOTA
2:30 p.m.	<u>Zell E. Peterman</u> and P.K. Sims--MIDDLE PROTEROZOIC EVENTS IN NORTHEASTERN WISCONSIN AND ADJACENT MICHIGAN AS DEFINED BY RB-SR BIOTITE AGES
2:50 p.m.	COFFEE BREAK

FRIDAY, APRIL 27, 1984 - continued

- 3:10 p.m. Joseph J. Mancuso, Robert Brown, James Harrison,
 Alan Maharidge, Richard Pennington and
 Ronald Walden--GEOLOGY OF THE GROVELAND MINE,
 FELCH DISTRICT, MICHIGAN
- 3:30 p.m. Eugene C. Perry, Jr., S. Shen and C. Ueng--
 STABLE ISOTOPE EVIDENCE OF METAMORPHISM AND
 HYDROTHERMAL ALTERATION, NEGAUNEE IRON
 FORMATION, MICHIGAN
- 3:50 p.m. Jeffrey K. Greenberg--MAGMATISM AND THE BARABOO
 INTERVAL: BRECCIAS, DIKES, AND METASOMATISM
- 4:10 p.m. Bruce A. Brown--LITHOLOGIC DIVERSITY AND THE
 SEDIMENTARY-TECTONIC ENVIRONMENT DURING
 DEPOSITION OF BARABOO INTERVAL (1760-1500 MY)
 ROCKS
- 5:30 p.m. FIELD TRIP II DEPARTS FOR IRON MOUNTAIN, MICHIGAN
 FROM THE HOLIDAY INN. (Overnight in
 Dickinson Inn.)

SATURDAY, APRIL 28, 1984

- 8:00 a.m. - 5:00 p.m. FIELD TRIP II: EARLY PROTEROZOIC TECTONOSTRATIGRAPHIC
 TERRANES OF THE SOUTHERN LAKE SUPERIOR REGION by
 W.L. Ueng, D.K. Larue, R.L. Sedlock, and D.A. Kasper,
 Department of Geology, Stanford University,
 Stanford, California
- 8:00 a.m. - 5:00 p.m. FIELD TRIP III: GEOLOGY OF THE WAUSAU SYENITE COMPLEX,
 by Paul E. Myers, Geology Department, University of
 Wisconsin-Eau Claire, Eau Claire, Wisconsin

ABSTRACTS

Nd and Sr Isotopic Studies of the Quinnesec and Hemlock Formations in Northeastern Wisconsin and Adjacent Michigan

WARREN BECK (Dept. of Geology and Geophysics, University of Minnesota, Minneapolis, MN 55455)

The Proterozoic Penokean events of the southern Lake Superior region have recently been interpreted in terms of Phanerozoic plate tectonic models. Two fundamentally different terrains may be found juxtaposed in the northern Wisconsin-Upper Michigan region. The northern terrain has been interpreted to represent a continental margin, while the southern volcano-plutonic terrain is interpreted to represent an island arc. The Penokean Orogeny is interpreted to represent a collision event between these two terrains. The following isotopic study supports the contention that such models are applicable to the Penokean events.

REE patterns from tholeiitic basalts and gabbros from the southern terrain yield extremely LREE depleted signatures (Klaus Schultz, 1983) similar to those of MOR basalts. In contrast, tholeiites and gabbros from the northern terrain yield LREE enriched patterns (Fox, 1983), resembling continental flood basalt signatures.

Tholeiitic basalts and gabbros from the southern terrain define a $^{143}\text{Nd}/^{144}\text{Nd}$ isochron with $\epsilon_{\text{Nd}} = 4.17 \pm .95$, and an age of 1871 ± 57 my (2σ). The age is interpreted as a crystallization age and is similar to U/Pb ages of 1860 my obtained for several granitic plutons found in the southern terrain. In contrast, the basalts and gabbros from the northern terrain do not define a Nd isochron. Other isotopic data suggest however that they are about the same age or slightly older. Calculating initial ratios for 10 samples from the northern terrain yields an average $^{143}\text{Nd}/^{144}\text{Nd}$ initial of $\epsilon_{\text{Nd}} = -2.04 \pm 4.2$. This suggests that the source regions for the two terrains are distinct, with the southern tholeiites coming from a LREE depleted mantle source.

The Rb/Sr systematics reveal a later thermal event of unknown origin, but support the above thesis regarding the different source regions for the two terrains. The northern terrain yields a Rb/Sr errorchron age of 1550 ± 197 my (2σ), and an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.70572 ± 14 (2σ); whereas the southern terrain suite yields an age of 1573 ± 113 my (2σ), and an initial $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.70258 ± 8 (2σ). Both ages overlap the age of emplacement of the very large anorogenic Wolf River Batholith, and span the age of a widespread yet poorly understood low-grade thermal event which affected much of the region about 1700-1650 my ago.

The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (0.70572 ± 14) from the northern terrain is contained within the field for continental crustal source regions on an $^{87}\text{Sr}/^{86}\text{Sr}$ evolution diagram. It is not clear however whether this reflects the characteristics of the source regions of the Hemlock basalts, or rather is a reflection of the isotopic composition of the fluids which reset the Rb/Sr systematics. In contrast, the initial $^{87}\text{Sr}/^{86}\text{Sr}$ from the southern terrain (0.70258 ± 8) is radically different from that of the northern terrain, and is contained within the

field for source regions for basalts. Hence the Rb/Sr systematics are consistent with the Nd isotopic systematics. In particular they are consistent with the thesis that the two terrains evolved from fundamentally different source regions, and that the northern terrain tholeiites and gabbros were generated from a source region with a strong continental affinity, while the southern region tholeiites and gabbroic sills were generated from a reservoir which strongly resembles the modern day MORB source regions. For these reasons we suggest that this data is consistent with the existence of a suture zone between these two terrains, and that this data supports the above mentioned plate tectonic model of the Penokean events.

Lithologic diversity and the sedimentary-tectonic environment
during deposition of Baraboo interval (1760-1500my) rocks.

Bruce A. Brown (Wisconsin Geological and Natural History Survey, 1815
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The Baraboo interval is represented by clastic and chemical sediments deposited in an epicratonic environment between major anorogenic magmatic events 1760 and 1500 m.y. ago (Greenberg and Brown, 1984). This period of magmatism and sedimentation followed the orogenesis and cratonization of the Penokean Orogeny about 1850 m.y. ago. Recent geologic mapping in central Wisconsin, and subsurface studies in southern Wisconsin have produced significant new data on Baraboo interval rocks, their environment of deposition, and their tectonic history.

The Baraboo interval is best known for red quartzites, such as the Barron, Sioux, and Baraboo. New mapping and reexamination of known exposures, cores and cuttings show quartzite in association with argillite, carbonaceous slate, bedded chert, arkose, siliceous and carbonate iron formation, polymictic conglomerates, and volcanogenic sediments.

At Baraboo, and in the subsurface of southeastern Wisconsin, argillaceous rocks, iron formation, and micaceous quartzite occur in the upper part of the section, above the red quartzites. In parts of central and northern Wisconsin, these lithologies commonly occur within a few meters of the base of the section. The areal and vertical distribution of lithologies across Wisconsin suggests a complex depositional environment in which local heterogeneities, structural or topographic, controlled the distribution of coarse sediments and allowed contemporaneous deposition of mature quartz sandstones in one area and deposition of shales and chemical sediments in another. The presence of volcanogenic sediments suggests that local rhyolitic volcanism may have occurred contemporaneously with sedimentation, or that fresh volcanic rocks were exposed to erosion within the depositional basin.

The dominant deformational structures in the Baraboo interval rocks are often folds overturned to the south. Deformational intensity increases to the east and southeast. Greenschist facies metamorphism is common throughout the area of exposure, with higher grade assemblages evident only in areas where these rocks are intruded, particularly by granitic rocks of 1500 my age.

The Baraboo interval was a time of anorogenic tectonic activity. Early in the interval, rhyolitic volcanism and sedimentation were probably contemporaneous. Anorogenic regional uplift at around 1630 m.y. years ago may have been important in the initiation of deformation of the volcanic and sedimentary rocks, as well as generation of the alkali-line magmas which intruded the already deformed rocks at around 1500 my.

Greenberg, J.K., and B.A. Brown, 1984, Cratonic sedimentation during the Proterozoic: an anorogenic connection in Wisconsin and the upper midwest, in press, Journal of Geology, March 1984.

Early Proterozoic structures of Northeastern Wisconsin
as constraints on Penokean tectonic models

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J.K. GREENBERG (Wisconsin Geological and Natural History Survey, 1815 University Avenue, Madison, WI 53705)

The Niagara tectonic zone has been described by several authors as a suture along which a Proterozoic volcanic arc terrane (Penokean volcanic belt) to the south, was accreted onto the southern margin of an Archean craton during the Penokean Orogeny. In modern plate tectonic concepts this interpretation implies compressional deformation which should be identifiable on both sides of the axis of suturing. Recent geological maps of the region show that indeed structural trends on both sides of the Niagara zone are roughly parallel. However, analysis of structural data collected in mapping of the Penokean volcanic belt has raised serious questions regarding the nature of the suturing process and the strict applicability of modern plate tectonic analogues.

The structural pattern within the volcanic belt is characterized by tight to isoclinal folds and a regional foliation which strike roughly parallel to the belt margins. Lithologic contacts and foliation are generally parallel, and steep dips (70° to vertical) are predominant. The trends of these regional structures are locally reoriented around large gneissic granitoid complexes, and smaller granitic plutons. Although these complexes may include many different granitoid phases, internal foliation patterns are generally concentric. Regional foliation generally does not pass through the granites. Exceptions are cases where plutons are located adjacent to major faults or smaller plutons are between larger complexes. Steeply plunging folds which re-fold the earlier regional foliation, and strong subvertical lineations are commonly developed near the granitic contacts and between closely spaced plutons. Greenschist facies metamorphism has affected the entire belt, and higher grade metamorphic assemblages are developed around intrusive rocks. Isotopic data suggest that the granitoid rocks are roughly the same age as the volcanic rocks, with no indication of older basement remobilization as is typical in the mantled gneiss domes of the terrane to the north. The overall picture is of a tectonic-metamorphic pattern very similar to that of Archean granite-greenstone terranes, only in younger rocks (Greenberg and Brown, 1983; Brown and Greenberg, 1983).

Available data suggest that higher-grade metamorphic assemblages and increased strain intensity are functions of location with respect to intrusive bodies rather than proximity to the proposed suture. There is no evidence of an increase in either deformational intensity or metamorphism across the belt towards the Niagara zone. Structures within the Niagara zone suggest vertical movement, rather than horizontal thrusting typical of most Phanerozoic sutures.

The arguments presented above suggest that the Niagara tectonic zone may be more analogous to subprovince boundaries within the Superior Province than to a modern zone of continental-scale collision. All of the known Penokean volcanic rocks are chemically more like modern magmas than Archean greenstones (Greenberg and Brown, 1983). Both the chemistry and the structural style of this terrane suggest a tectonic environment transitional between modern plate-margin convergence and Archean block-boundary interactions.

Brown, B.A., and J.K. Greenberg, 1983, Gneiss Domes and Not so Gneiss Domes in the Penokean terranes of Northern Wisconsin, (abs.) Twenty-ninth Institute on Lake Superior Geology, Houghton, p. 6.

Greenberg, J.K., and B.A. Brown, 1983, Lower Proterozoic Volcanic Rocks and their setting in the Lake Superior District, in L.G. Medaris, Jr., ed. Early Proterozoic Geology of the Great Lakes Region, Geological Society of America, Memoir 160, p. 67-84.

Basement Cover Relations in the Marquette and Republic Districts, Michigan

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MEYER, R. O. (Lagoven S.A., Org. Geologia, Apartado 234, Maturin, Edo. Monagas, Venezuela, Zona Postal 6201)

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It is proposed that the Archean basement between the Marquette Trough and the Republic Trough behaved as an essentially rigid material during both the subsidence and the deformation associated with the Penokean Orogeny.

In the subsidence phase the basement fractured into several rift bounded troughs in which sediment accumulated to greater thickness than the surrounding areas, particularly the Banded Iron Formation.

During subsequent compression deformation was effected in the basement by ductile shear along mafic dikes which were intruded during the rifting. Using the sense of shear on these dikes it can be shown that the maximum principal stress during closing was east of north and was focussed near the trough margins, becoming normal to them, a feature observed in the elastic deformation of plates with holes in them. In addition the data shows that the maximum shear strain occurs on dikes which are approximately 45° to the maximum principal stress direction, a feature consistent with non-rotational deformation by simple shear on the dikes.

This type of deformation resulted in translation of rigid blocks of basement with no internal distortion. The overlying sediments responded accordingly. At the margins of the troughs reactivated faults resulted in the basins closing like the jaws of a vice producing high strain in the troughs and relatively low strain on the platforms in between. One locality on the south side of the Republic Trough exemplifies this. In flat lying uncleaved Kona Formation shales the reduction spots are flattened in the bedding. In the adjacent tilted horizons the spots are oblique to the bedding with the $\lambda_1\lambda_2$ plane lying parallel to cleavage.

Microstructures in the Multiply Deformed Slate of the Thomson Formation,
East-Central Minnesota

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The Early Proterozoic Thomson Formation consists of intercalated slate, slaty greywacke and metagreywacke units. The formation was multiply deformed during the Penokean orogeny (1900-1800 m.y.) resulting in two major phases of folding with axial-planar foliation. The second deformation affected the entire study area, whereas evidence of the first deformation is found only in the extreme southern portion of the study area. Later minor deformation, possibly related to Keewenawan rifting, resulted in the development of kink-bands in some areas.

In the southernmost areas affected by both major Penokean deformations a crenulation cleavage has formed in the fine-grained slates. Microstructural evidence suggests that the crenulation cleavage developed by a solution-deposition process similar to that proposed by Gray and Durney (1979). The principle behind the pressure solution process is the solution transfer of soluble minerals from sites of high chemical potential to sites of low chemical potential. The difference in chemical potential can be directly related to stress variations around microfolds (crenulation-folds). The grains along the limbs are subject to a higher normal stress (and thus a higher chemical potential) than the grains in the hinge zones. Soluble species (such as quartz) are then transferred from the limbs to the hinge zones (or out of the system into quartz veins) causing the passive concentration of relatively insoluble phyllosilicates into mica-rich zones (zonal crenulation cleavage) or into distinct mica-rich cleavage seams (discrete crenulation cleavage) in the former limb zones.

Kink-bands are common in the slates at the type locality at Thomson Dam. Kink-bands can be defined as small-scale monoclinal folds having planar limbs and angular hinge zones normally found in rocks with a definite planar anisotropy (such as cleavage). Several models have been proposed to explain the formation of kink-bands. Two models that have characteristics found in the Thomson Formation are the rotation model and the joint-drag model. The rotation model proposes that as deformation proceeds, the foliation within the kink-band is rotated through increasing angles. Since the foliation remains hinged at the kink-band boundary it is geometrically necessary for the foliation to part or dilate as rotation occurs thus creating volume expansion. As rotation passes a critical point the foliation begins to close. It is possible, however, for the spaces within the dilated foliation to be filled by precipitating minerals (such as quartz or calcite) thus 'jamming' the kink-band at an intermediate stage. The joint-drag model proposes that the foliation is actually broken and offset by shear along the kink-band boundary during deformation. Further deformation causes rotation of the kinked foliation accompanied by slip along individual folia within the kink-band. Triangular-shaped voids (which later may be filled with quartz or calcite) develop along the kink-band boundary causing volume expansion of the rock.

Kink-bands of the Thomson Formation contain characteristics of both models indicating that aspects of both models were probably in operation. The foliation can be seen as discontinuous (sheared) or continuous across the kink-band boundary even within different parts of the same kink-band. Triangular-shaped voids and dilation zones between individual folia (both now filled with quartz) are present indicating volume expansion of the rock. Since volume expansion of the rock in a horizontal direction is involved, the kink-bands must have formed at a high structural level where confining pressures were low. They are also thought to have formed late in the structural history of the area, possibly as a result of Middle Proterozoic Keewenawan activity (1100 m.y.).

Reference

- Gray, D. G. and Durney, D. W., 1979, Crenulation cleavage differentiation: implications of solution-deposition processes: *Journal of Structural Geology*, Vol. 1, No. 1, pp. 73-80.

Geology of the Rainy Lake area, northern Minnesota-revisited

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Recent geologic mapping of the 2,700-m.y.-old Rainy Lake area of northern Minnesota provides new insight into the tectonic development of the area. The Rainy Lake area trends northeast across the Minnesota-Ontario international border, and lies within the western extension of the Wabigoon greenstone belt of the Superior province. The area is bounded on the south by the Rainy Lake-Seine River fault and on the north by the Quetico fault. The Minnesota segment of the area is composed of volcanic and subvolcanic intrusive rocks intercalated with volcanoclastic, epiclastic, and chemical sedimentary rocks. These rocks grade upward into volcanogenic graywacke. The volcanic rocks are bimodal in composition: the mafic rocks have tholeiitic affinity and the felsic rocks have calc-alkaline affinity. In Minnesota all of the rock types have been metamorphosed to upper greenschist facies.

The Minnesota portion of the Rainy Lake area has been affected by three major deformation events. The first was large-scale folding that produced an S_1 schistosity subparallel to bedding (S_0), and southwest-plunging F_1 parasitic folds and L_1 mineral lineations. The second event produced tight, upward-facing, asymmetric folds, 1-3 km in scale, an S_2 penetrative cleavage, and northeast-plunging F_2 parasitic folds and L_2 mineral lineations. The last deformation event produced the Rainy Lake-Seine River fault.

In Minnesota, the upward-facing F_2 folds and upright stratigraphy contrast with the downward-facing F_2 folds observed in Ontario. Poulsen and others (1980) concluded that the stratigraphic succession to the northeast in Ontario is inverted, probably as a result of large-scale recumbent folding. Another contrasting feature is the metamorphic grade of graywacke units; those in Minnesota being greenschist facies, whereas those in Ontario being sillimanite-bearing amphibolite facies.

A structurally consistent model for the region places the rocks in Minnesota on the upper (upward-facing) limb, and the rocks in Ontario on the lower (downward-facing) limb of a major F_1 recumbent fold. This hypothesis suggests that the higher metamorphic grade in Ontario could reflect the higher temperature and pressure conditions experienced by the lower, more deeply buried limb of the recumbent fold (fig. 1). The new structural model differs markedly from that of Ojakangas (1972), who proposed that the inconsistencies in stratigraphy and structural style were caused by the juxtaposition of internally coherent, fault-bound structural blocks.

Although the structural model proposed here satisfies the geometrical relationships, several problems remain. For example, the location of the F_1 recumbent fold axis is not known, nor is there any documented evidence of thrust faulting associated with nappe structures that might have been developed during the F_1 recumbent folding event. Only through testing and revision of the proposed structural model by further detailed geologic mapping can the structural development of the Rainy Lake area be fully resolved.

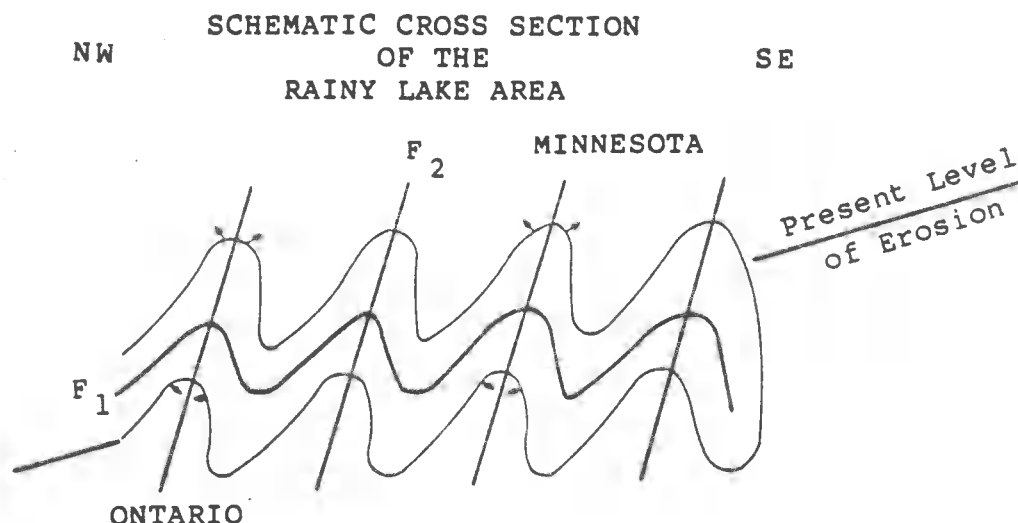


Figure 1. Schematic cross section of the Rainy Lake area. The Minnesota rocks are on the upright limb, whereas the Ontario rocks are on the overturned limb of a regional F_1 recumbent fold(s). In Minnesota the F_1 fold has been refolded by asymmetric F_2 folds that have steep northwest-dipping fold hinges.

References cited

- Ojakangas, R.W., 1972, Rainy Lake area: in Sims, P.K., and Morey, G.B., eds., *Geology of Minnesota: a Centennial Volume*, Minnesota Geological Survey, p. 162-171.
- Poulson, K.H., Borradaile, G.J., and Kehlenbeck, M.M., 1980, An inverted succession at Rainy Lake, Ontario: *Canadian Journal of Earth Sciences*, v. 17, p. 1358-1369.

Mineralogy of Pegmatites in the Wausau Pluton,
Marathon County, Wisconsin

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The Wausau Pluton is a quartz-rich phase of granitic quartz syenite-pyroxene amphibole syenite which is exposed at Wausau, Marathon County, Wisconsin. The age of the body was determined to be $1,520 \pm 25$ m.y. (Van Schmus, 1980). The pluton is cut by numerous pegmatitic dikes of generally gentle dip. The Mirolitic cavities in these dikes yield an astonishing array of accessory minerals, particularly Fe, Ti, Be, REE minerals with lesser amounts Sb and Pb bearing species and rarely those containing B, Nb, Ta. Variations in pocket constituents, paragenesis, and morphology occur widely, not only from pegmatite to pegmatite but also from pocket to pocket within the same pegmatite. Pocket rupture, thermal shock and metasomatic effects are very often seen.

Several types of typical assemblages can be distinguished:

- a. Simple paragenesis of pockets in small dikes:
Microcline, albite and quartz are the bulk minerals with few accessories like siderite (pseudomorphously replaced by other Fe minerals), hematite, hisingerite, phenakite, bertrandite, anatase.
- b. Complex paragenesis of pockets in larger dikes:
Besides the bulk minerals as above, a considerable variety of accessories like sulfides and sulfosalts (pyrite, jamesonite, boulangerite, and others. These are unaltered only if protected in other mineral phases.), siderite (replaced), phenakite, bertrandite, anatase, rutile, brookite, fluorite, F-apatite, REE-minerals, especially a REE-rich cheralite and others.
- c. Simple paragenesis of vuggy intermediate zones:
Besides the bulk minerals large amounts of hematite and less commonly pyrite (replaced), zircon, fluorite, F-apatite are found.
- d. Paragenesis of late stage formation in solution etched zones near pockets with quartz selectively removed (and sometimes redeposited):
Besides the bulk minerals this environment is especially dominated by Ti oxides (anatase, brookite, rutile) and often accompanied by ilmenite, zircon, bertrandite, cheralite and others.

This paper is based on data collected during excavation of over 760 pegmatite pockets in the Wausau Pluton, therefore, it should be a fairly representative description.

PRECAMBRIAN GEOCHRONOLOGY IN MINNESOTA

S. S. GOLDICH (Department of Geological Engineering, Colorado School of Mines, Golden, CO 80401)

Orogeny has been defined simply as "mountain building". When geologists began studying simple mountains in detail, they found that a number of geological processes were involved. These can be defined simply as mountain-building or orogenic processes, but the only thing that most geologists seem to agree on is that there is nothing simple about mountain building or orogeny.

The early classification of the Precambrian rocks of Minnesota, summarized by Grout et al. (1951, GSA Bull. 26, 1017), divided the succession into three major groups separated by two "great" unconformities. These were cut on complexes of batholithic intrusives in folded metasedimentary and metavolcanic rocks related to two periods of orogeny.

K-Ar, Rb-Sr, and early U-Pb age determinations failed to resolve the Laurentian from the younger Algoman orogeny. The age measurements revealed a complex geological history and indicated that the time interval was small, about 50 m.y. Within recent years notable improvements have been made in analytical techniques and in the interpretation of radiometric ages, particularly U-Pb ages determined on zircon and titanite. Late- to postkinematic Algoman granites, as defined by Lawson and the Minnesota geologists, are dated at 2,680 Ma and the Laurentian orogeny at 2,735 Ma. The Laurentian may be regarded as an early phase of the Algoman orogeny as has been suggested by a number of writers, but for local use, the distinction is useful.

New U-Pb data from east-central Minnesota, likewise, provide better resolution of the Penokean orogeny (1,800-1870 Ma), similar to the interval found in Wisconsin by Van Schmus and others.

Magmatism and the Baraboo Interval:
Breccias, Dikes, and Metasomatism

JEFFREY K. GREENBERG (Wisconsin Geological and Natural History Survey,
Madison, WI 53705)

In Wisconsin breccias are common features in many of the known exposures of quartzites deposited during the Baraboo interval. The breccia matrix is typically white vein quartz and partial voids containing clay and quartz crystals. Dalziel and Dott (1970) previously attributed the breccias to "explosive hydrothermal activity", an interpretation preferred over a fault origin. Fluid inclusions in quartz crystals indicate temperatures of formation greater than expected from sedimentary fluids except under ambient conditions at depths greater than 3 km below the Earth's surface. This represents an unlikely environment for the development of brittle fracturing and undeformed voids. However, we have observed that all the breccias are associated with intrusions including massive granite and diorite, granitic dikes and pegmatites, and sometimes basaltic-andesitic dikes. Most of the brecciated quartzites also show evidence of metasomatism (late magmatic?). Observed metasomatic features include: clay segregations in breccia which apparently contain feldspar pseudomorphs; unaltered feldspar porphyroblasts in altered quartzite; tourmaline-quartz veinlets in quartzite; and books of muscovite (to 1 cm diameter) crystallized in vein quartz and replacing other minerals in quartzite. The above examples of intrusion and metasomatism occur in various combinations at the breccia exposures of Baraboo, Necedah, Battle Point, Waterloo, Rib Mountain, and Hamilton Mound.

Our present interpretation of the breccias is that they are analogous to the stockwork of quartz veins produced around the upper levels of porphyry-copper mineralized plutons. During magma intrusion, the roof rocks (quartzite) were fractured and soaked in hydrous granitic fluids. The fluids and their particular effects vary with distance from source plutons. Thus, as in some Wisconsin examples, quartz veins and breccias grade into actual pegmatite dikes as intrusions are approached.

The coincidence of quartzite breccias, intrusions, and metasomatism suggest controversial relationships which have often gone unrecognized. If isotopically dateable, the intrusions could specify minimum ages of units within the Baraboo interval. Available age data are confusing, but the quartzite exposures are probably somewhere between 1760 and 1500 m.y. old.

Dalziel, I.W.D., and Dott, R.H., Jr., 1970, Geology of the Baraboo District, Wisconsin: Wisconsin Geological and Natural History Survey, Information Circular 17, 164 p.

Mobilization of Uranium and Thorium
Within the Republic Metamorphic Node, Northern Michigan

ROBERT L. HACKENBERG (Conoco, Inc., Lafayette, Louisiana)
GREGORY MURSKY (Dept. of Geol. and Geop. Sciences, University of
Wisconsin-Milwaukee, Milwaukee, Wisconsin 53201)

The paper summarizes the results of uranium and thorium neutron activation analysis of 150 samples from regionally metamorphosed Precambrian rocks, which comprise the Republic metamorphic node, centered around the city of Republic, northern Michigan. Six lithologic rock units, whose metamorphism can be delineated wholly or partly by chlorite, biotite, garnet, staurolite, and sillimanite isograds, were considered.

The data, which is summarized in Figure 1, indicates that mobilization of uranium might have taken place in rock units which have been subjected to higher grades of metamorphism. This is particularly evident in metagranodiorite, shale, and metadiabase. The trends for granitic gneiss and metavolcanics are inconclusive because these two rock units do not appear in areas represented by low or intermediate grades of metamorphism.

The concentrations of thorium (Figure 2) in general follow the trends of uranium concentrations and suggest that at higher grades of metamorphism there has been some mobilization of thorium.

The study indicates that higher grade metamorphism may play an important role in the mobilization of uranium, and perhaps thorium, and that it may contribute to the formation of ore-forming fluids. Concentration and precipitation of uranium from such fluids may result in economic uranium deposits.

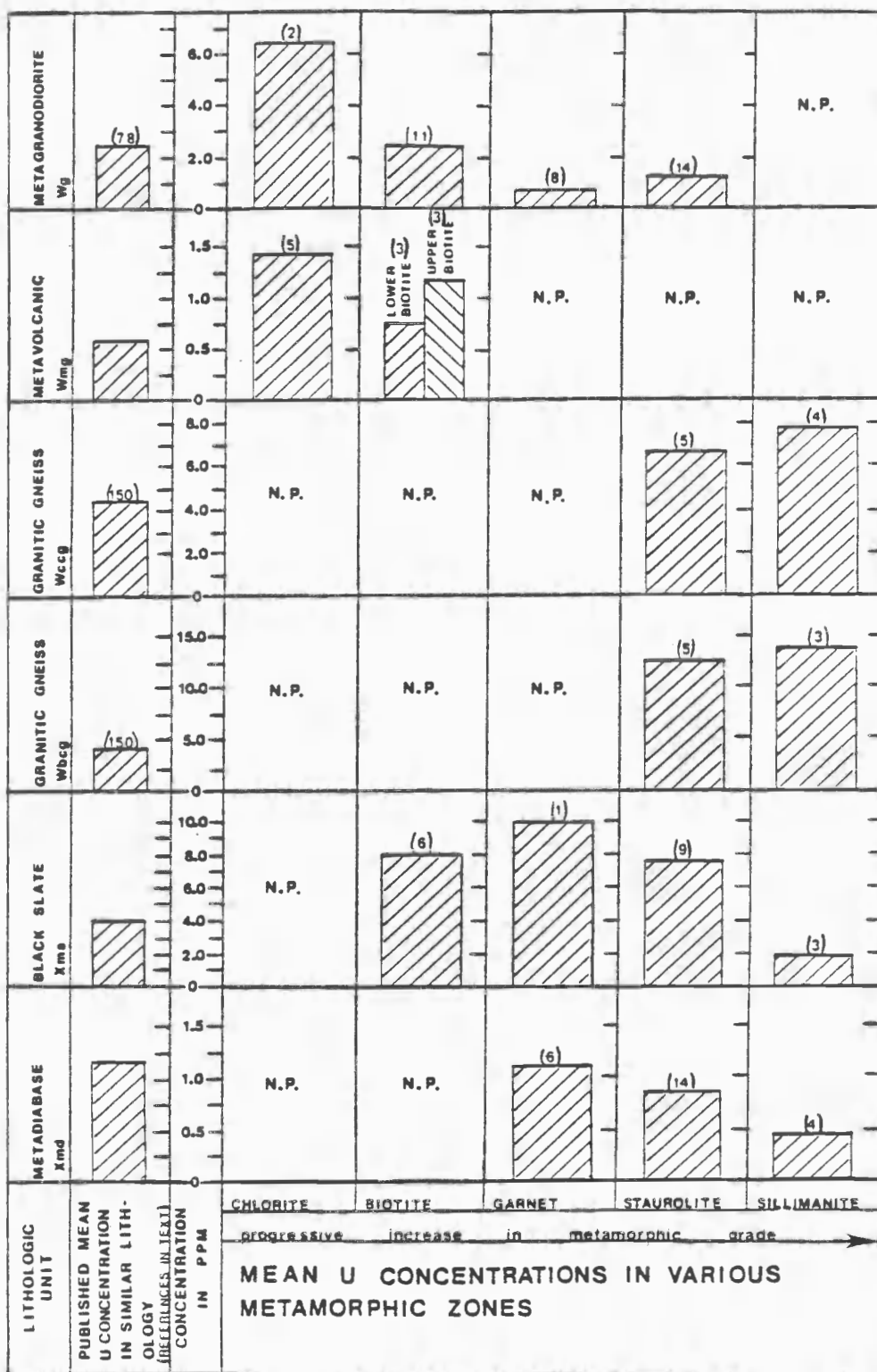


Figure 1. N.P. signifies lithology not present in that metamorphic zone. Numbers in parenthesis are number of samples analyzed.

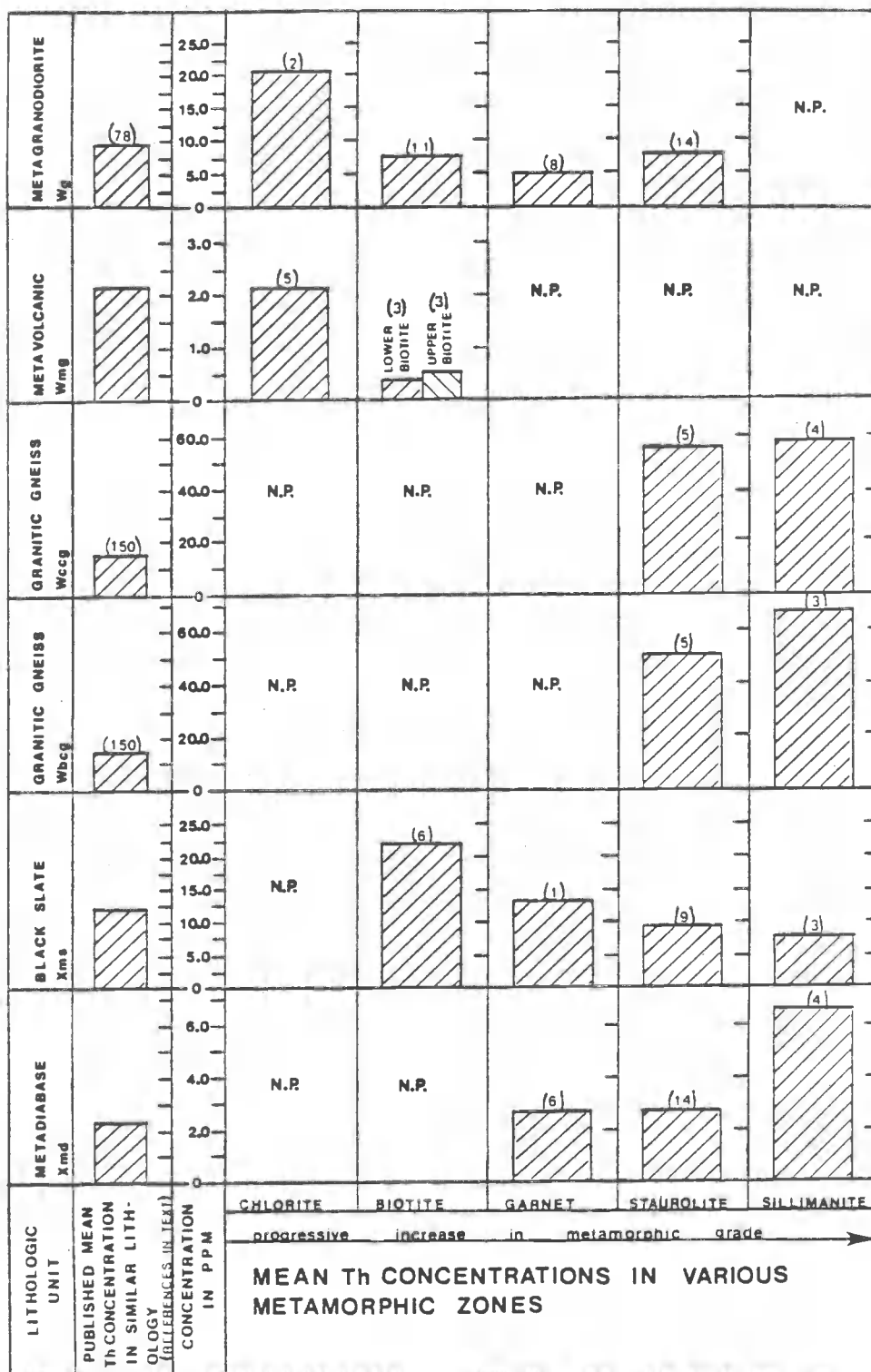


Figure 2. N.P. signifies lithology not present in that metamorphic zone. Numbers in parenthesis are number of samples analyzed.

Comparison of Middle Proterozoic Iron Oxide Rich Ore Deposits,
Mid-Continent, U.S.A., South Australia, Sweden,
and the Peoples Republic of China

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Middle Proterozoic (1.8-1.1 Ga) iron oxide rich deposits comprise a diverse family of economically important, multicommodity ore deposits which appear genetically related. The genetic grouping of these deposits (previously not well described) appears to fill a gap (or transition zone) in many time-tectonic ore deposit classifications between Lower Proterozoic (2.5-1.8 Ga) banded iron formations (BIF) and Phanerozoic iron oxide deposits. Common features of these iron oxide deposits include:

- (1) iron contents greater than 20% Fe as magnetite and/or hematite;
- (2) anomalous to economic concentrations of base metals (Cu, Co, Mo), precious metals (Au, Ag), and U;
- (3) associated geochemical enrichment (occasionally economic) in LREE, Ba, P, F, and Th;
- (4) intimate primary mixture of iron sulfides and hematite and/or magnetite;
- (5) host rock and mineralization ages between 1.8 and 1.1 Ga;
- (6) close spatial and temporal relationship to anorogenic felsic dominated, bimodal volcanics and intrusives (rapakivi granites and ferrodiorites) of lower crustal and mantle origin;
- (7) ore deposition in an upper crustal subvolcanic environment and/or intracratonic or marginal (tensional) sedimentary basins;
- (8) very large tonnage, commonly exceeding one billion tons. Examples include the Kiruna District, Sweden (Kiirunavaara, Rektorn, and Hauki deposits), Baiyan OBo, Inner Mongolia, Peoples Republic of China (PRC), Pilot Knob-Pea Ridge, Missouri, and Olympic Dam, South Australia.

The Middle Proterozoic iron oxide rich deposits are found in marginal to intracratonic, tensional basins overlying Lower Proterozoic rocks on the margins of Archean shields (Churchill, Gawler, Baltic, North China). The basins contain arkoses, sandstones, and minor(?) carbonates (sebkha?), volcanoclastics, and felsic volcanics. Sedimentary exhalative (SEDEX) hematitic iron formations (+ Cu, Co, Mo, Au, Ag, U, LREE, P, Ba, F) are interbedded with these sediments and may form ore deposits (Pilot Knob Outcrop, Olympic Dam, Baiyan OBo, Hauki). Related subvolcanic magnetite and magnetite-hematite ore deposits (+ Cu, Co, Mo, P, F) may be associated with these basins (Pea Ridge, Pilot Knob Subcrop, Kiirunavaara).

A review of the geochemistry of these iron oxide rich deposits suggests a more or less continuous differentiation series. Overall, there are general decreases in TiO_2 and P_2O_5 (fluorapatite) with corresponding increases in LREE, base and precious metals, U (Th), F, and Ba. These trends are compatible with a continuing differentiation of an iron rich immiscible liquid with decreasing P and T (and increa-

sing oxygen fugacity) conditions. The final ore deposit composition and tectonic position of the iron oxide rich deposits is related to when and where in the crust liquid immiscibility occurs and when and where the iron oxide rich differentiate is released.

These ore deposits formed during a global period of cratonic stabilization that followed the Archean greenstone belt style of tectonics. The ore deposits may be related to other lower crustal rock types known to have formed during the Middle Proterozoic, i.e., anorthosite massifs-rapakivi granites and their associated magmatic segregation Fe-Ti-P ore deposits (Allard Lake, Adirondacks, Nelson, Va). Production and differentiation of immiscible iron oxide rich liquids during anorthosite emplacement may be the common denominator for the origin of upper and lower crustal iron oxide deposits. Passive emplacement of anorthosites produces uplift and extension to form marginal and intracratonic basins. Accompanying lower crustal partial melting generates rapakivi granite suites and related areally extensive felsic volcanics. Coeval, alkalic, intermediate and mafic volcanics (minor) and intrusions are also related to anorthosite emplacement. Related Upper Proterozoic (1.1-0.5 Ga)-Lower Paleozoic anorogenic events are represented by abortive rifting (Keeweenawan, Adelaidean Geosyncline, Oslo Graben) and/or alkalic plutonism (Delamerian Orogeny, South Australia and Inner Mongolia). Paleozoic and younger carbonatites and kimberlites may be one of the last events to characterize this cratonization process.

The central U.S., from Missouri to the Great Lakes region, has several areas of favorable rock types and tectonic settings compatible with these ore deposits. Careful geophysical modeling combined with geochemical and geologic interpretation should lead to identification of drillable targets for another of these economically important, giant ore deposits.

Penokean tectonics: Constraints from structural geology in east-central Minnesota

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In the past decade there have been several plate tectonic models for the early Proterozoic Penokean orogeny. These all involve convergent plate boundaries and some suggest collision, or multiple collision. Other tectonic models which suggest that the Penokean was an intracratonic event emphasize the role of basement. They suggest that basement was remobilized, and high heat flow concentrated along a fundamental boundary in the basement, the Great Lakes Tectonic Zone.

Recent structural studies of early Proterozoic rocks in east-central Minnesota have revealed several facts which constrain tectonic models of the Penokean orogeny: 1. In Minnesota, the Penokean orogeny involved two main phases of folding, each resulting in a penetrative tectonic fabric. 2. The first phase of deformation involved the development of northward-directed nappes in some areas, and was accompanied by a large flattening strain (Z approximately vertical) and a well-developed foliation. 3. The second phase of deformation led to the development of upright folds, and was accompanied by a horizontal shortening of over 60% (Z north-south and horizontal).

While these features could possibly be explained by decollement gravity-gliding off a rising diapir (McGrath Gneiss?) they are certainly also consistent with a convergent plate boundary environment, with a southward-dipping subduction zone. Further, the fabric within the McGrath Gneiss suggests that it was not a diapir, but was involved in the early phase of Penokean deformation, perhaps as nappe cores (as in Pennine Nappe Zone of the Alps) or as "embryonic nappe" basement shear zones, as recently suggested in the Helvetic Nappe Zone. Thus it seems that the structural evidence in east-central Minnesota is most easily accounted for by a convergent plate boundary model, consistent with the growing body of structural and petrologic evidence from Wisconsin and Upper Michigan.

The Role of Transcurrent Shear in Deformation of the
Archean Rocks of the Vermilion District, Minnesota

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Deformed and metamorphosed sedimentary and volcanic rocks of the Vermilion district occupy an east-west trending belt between higher grade rocks of the Vermilion Granitic Complex to the north and the Giants Range batholith to the south. All the measured strain, a cleavage, and a mineral lineation in this belt are attributed to the 'main' phase of deformation (D_2) that followed an earlier nappe-forming event (D_1), which left little evidence of fabric.

Previous work has assumed that the D_2 deformation resulted from north-south compression across the district, presumably related to diapiric intrusion of the batholithic bodies to the north and south. A number of observations now lead us to believe that a significant component of this deformation resulted from dextral shear across the whole region. Thus the Vermilion fault, a late-stage strike-slip structure that bounds the Vermilion district to the north, may simply be the latest, more brittle expression of a shear regime that was much more widespread in space and time. Features that are indicative of shear include ductile shear zones with sigmoidal foliation patterns, highly schistose zones with the development of shear bands, feldspar clasts or pyrite cubes with asymmetric pressure shadows, and the fact that the asymmetry of the F_2 folds is predominantly Z for at least 15 km south of the Vermilion fault.

The presence of a large component of simple shear may help explain additional structural features in a simpler way than otherwise possible. Just south of the Vermilion fault the cleavage locally becomes folded and a new spaced cleavage develops in a similar orientation to the old cleavage away from the folds. Rather than interpreting this as evidence for an additional episode of deformation, we consider it to be due to a single process of continuous shear: a foliation develops and after a large strain local perturbations result in folding of the old foliation and the development of a new one axial planar to the folds. The same type of perturbation can lead to the juxtaposition of zones of constrictional and flattening strains, a distinctive feature of the rocks of the Vermilion district otherwise hard to account for. The strain pattern requires a north-south component of shortening in addition to shear. The D_2 deformation in the Vermilion district can therefore be characterized as one of transpression: oblique compression between two more rigid (?) crustal blocks to the north and south.

Preliminary Paleomagnetic Results from the Baraboo Quartzite
and the Associated Rhyolite and Granite Inliers of
South Central Wisconsin

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The Proterozoic geology of Wisconsin represents a fairly complex succession of tectonic events. Of interest to this project is the suite of rhyolitic and granitic inliers of the Fox River Valley and the overlying Baraboo Quartzite which span the time from 1760 m.y. ago to 1450 m.y. ago.

A total of 50 samples of Baraboo Quartzite were collected from 15 sites on both sides of the Baraboo Syncline. The samples were subjected to both alternating field (A.F.) demagnetization and thermal demagnetization. The results indicate that stable remanence is carried by hematite and that the magnetization was set before the major folding of the syncline. The within-site directions are tightly clustered with K values ranging from 45 to 300, and α -95 values ranging from 18 to 5 degrees. The magnetic directions after unfolding cluster around an inclination of 29° and a declination of 190°. This gives a V.G.P. at about 28°S, 90°W which fits well with previously published North American Precambrian poles for the time range of 220 m.y. ago to 1650 m.y. ago.

We have also obtained preliminary results from several rhyolites from the Fox River Valley inliers. A.F. and thermal demagnetization studies show these samples to be magnetically softer, but reliable directions can be obtained. Two dominant pole positions are found; one is near 67°-87°N, 90°-150°W, and the other is near 2°-20°S, 90°-120°W. The first pole position is reasonable for 1630 m.y. ago, and the second is similar to the results for the Baraboo Quartzite.

Composite Magnetic Map of Wisconsin Precambrian from New Compilation
of Digital Aeromagnetic Data

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A composite magnetic contour map of the exposed Precambrian terrane of northern Wisconsin will be displayed for the first time. This map, at a scale of 1:250,000, was prepared from 94 aeromagnetic 15' quadrangle maps, which were compiled by Karl under a grant from the U.S. Geological Survey from data he obtained through a survey conducted during 1973-77. These 94 recontoured maps, at a scale of 1:62,500, will replace the set of 86 maps currently available from the Wisconsin Geological and Natural History Survey. The 20- and 100-gamma contours, unlike those of the previous set, are continuous and match at quadrangle boundaries. The myriad of detail on the composite magnetic map from this new compilation results in much more coherent patterns that highlight the contrasts in magnetic character of the underlying Precambrian terranes.

This magnetic map, in conjunction with simple Bouguer and filtered gravity maps of the same area, allows the westward extension of the three major tectonic belts or terranes proposed by Klasner and others (in press) for an area that includes the eastern part of the area shown in the composite magnetic map.

Klasner, J. S., King, E. R., and Jones, W. J., in press, Geologic interpretation of gravity and magnetic data for northern Michigan and Wisconsin: Society of Exploration Geophysicists Special Publication on the Utility of Regional Gravity and Magnetic Anomaly Maps.

Rb-Sr and Oxygen Isotope Systematics of Archean
Grey Gneisses of the southwestern Beartooth Mountains

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Rb-Sr and oxygen isotopic analyses were performed on samples of Archean grey granitic gneiss from the Cooke City region of the Beartooth Mountains, Montana. A whole-rock Rb-Sr isochron date for this unit of about 2700 m.y. is accompanied by an elevated initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7054. A more systematically-collected regional suite of these grey gneisses hints at an age in excess of 3 b.y., suggesting that an incompletely homogenized older component comprised a portion of the gneiss. Although whole-rock $\delta^{18}\text{O}$ values for the gneiss (average +8.00 ‰, range +6.98 to +10.03 ‰ relative to SMOW) tend to indicate a primary magmatic origin, the values are largely indistinguishable from $\delta^{18}\text{O}$ values of older metasedimentary units now found as rafts in the gneisses (+7.87 to +11.00 ‰, values which are lower than expected). A composite source would be more consistent with the Rb-Sr data and initial Sr ratio. The 2700 m.y. date reflects the age of a regional thermal event, pervasive throughout the Beartooth Mountains. A mixture of primary differentiated magma, perhaps contemporaneous with this thermal event, with assimilated older crustal material would account for both the strontium and oxygen isotope data.

Gravity models of gneiss domes and a granite pluton
in northeastern Wisconsin

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Three 2-dimensional density models of granitoid bodies have been prepared from gravity profiles in northeast Wisconsin. The profiles cross the Dunbar gneiss dome, another probable gneiss dome west of the Dunbar Dome, and the east lobe of the Hoskin Lake granite pluton which is considered a part of the Dunbar dome. Rock density analyses of 45 hand specimens collected by P.K. Sims indicate rocks of the domes, which are predominantly gneissic, are on the average of 0.21 gm/cm^3 less dense than the surrounding generally mafic volcanic rocks. The Hoskin Lake granite is an average of 0.30 gm/cm^3 less dense than the volcanic country rock. The density models indicate that the gneiss domes extend to a depth of 1.6 km (1 mile).

Gravity model studies of large post kinematic plutons (Bott and Smithson, 1967), of similar areal dimension as the gneiss domes, indicate that most of them are on the order of 10 km thick, much thicker than the domes and pluton of this study. They note, however, the Precambrian granitic bodies tend to be thinner than this and that they may be thinned by erosion. Although the gneiss domes of this study are likely synkinematic and not exactly the same as the granite plutons modelled by Bott and Smithson, they appear to be unusually thin. It is possible that varying densities with depth do not permit an accurate estimate of their true depth. On the other hand, the east lobe of the Hoskin Lake granite body is a discrete pluton. Its shallow depth and the fact that it lies within a prominent south dipping magnetic gradient suggests that it may be allochthonous and is truncated at depth. One possible scenario is that truncation occurred along south dipping thrust faults that are tectonically associated with the proposed Niagara suture which lies about four miles north of the Hoskin Lake pluton. If this is correct, then the gneiss domes may also be allochthonous features that are truncated at depth by thrust faults. Alternately, the shallow depths of the gneiss domes and granite pluton may be due to uplift and erosion.

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The Plate Tectonic History of North-central Wisconsin

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Recent mapping in north-central Wisconsin indicates the presence of three separate successions of Early Proterozoic volcanic rocks (Figure 1). Each succession has a distinct lithology, structural pattern, and metamorphic grade. These rocks and the Archean rocks to the south appear to be best explained by a plate tectonic model.

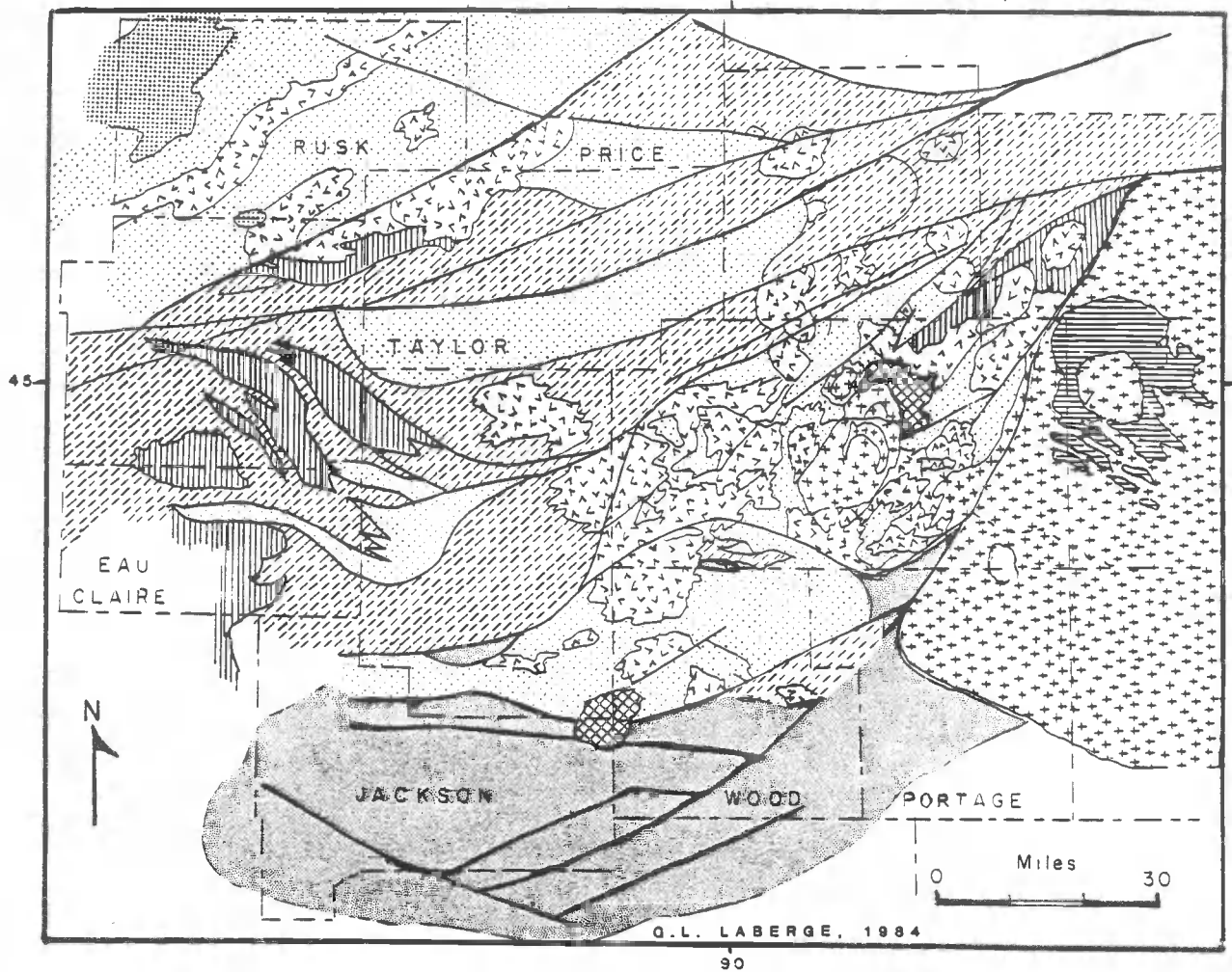
A widespread succession of Early Proterozoic quartzofeldspathic gneisses and amphibolite, derived mainly from subaqueous volcanic rocks is characterized by amphibolite-facies metamorphism and isoclinal folding about west- to northwest-trending axes. These metavolcanic rocks were intruded mainly by tonalites. Lithologies are characteristic of island arcs, and appear to have formed over a north-dipping subduction zone (Figure 2A).

Dated Archean gneisses are exposed to the south of these rocks in central Wisconsin, and farther south typical Archean "greenstone belt" lithologies of iron-formations and tuffs are found in drill cores and at the iron mine at Black River Falls. These Archean rocks are believed to be part of an older craton that collided with the Early Proterozoic island arc (Figure 2B). Metamorphism and deformation of the Early Proterozoic rocks was probably caused by the collision.

A younger sequence of Early Proterozoic volcanic rocks unconformably overlies the Archean and older volcanic arc in Marathon County and elsewhere. These rocks consist of subaqueous basalt to rhyolite that have undergone only greenschist-facies metamorphism, were deformed about steeply plunging northeast-trending axes, and were extensively intruded by epizonal granites. This succession is believed to have formed at a continental-margin over a southward-dipping subduction zone as the ocean basin to the north closed (Figure 2C). The Niagara fault zone is interpreted to be the boundary between these volcanic assemblages and platform sedimentary rocks on the Superior craton to the north (Figure 2D). Deformation and metamorphism associated with the collision of these volcanic belts with the Superior craton represent the Penokean Orogeny. Dozens of ultramafic bodies occur along the boundary between the Archean and Early Proterozoic rocks in Central Wisconsin. In addition to numerous sulfide occurrences (mostly small) in both Early Proterozoic successions, at least four localities with significant gold mineralization are known in the proposed collision zone in Central Wisconsin.

A third and youngest cycle of Early Proterozoic igneous activity is represented by rhyolites at Wausau and Cary Mound which unconformably overlie the older sequences, are gently folded about axes plunging 10° - 20° west, and are virtually unmetamorphosed. These rocks--welded tuffs, lahars, and flow-banded rhyolites--are typical caldera type rocks analogous to basin-and-range volcanic rocks in the Western United States. The basin-and-range rocks may be related to rifting.

Later faulting and emplacement of the Wolf River batholith and related syenites during the Middle Proterozoic has further complicated the geology.



EXPLANATION

MIDDLE PROTEROZOIC		EARLY PROTEROZOIC	
	GRANITE AND SYENITE		QUARTZITE
	ANORTHOSITE		RHYOLITE
			GRANITOID ROCKS
			GREENSCHIST FACIES VOLCANICS
ARCHEAN			QUARTZOFELDSPATHIC GNEISS
	GNEISS, GREENSTONE AND GRANITE		AMPHIBOLITE

Figure 1. Geological map of the Precambrian of north central Wisconsin showing the fault-bounded blocks of greenschist-facies volcanic rocks alternating with amphibolite-facies volcanic rocks and the Archean rocks to the south.

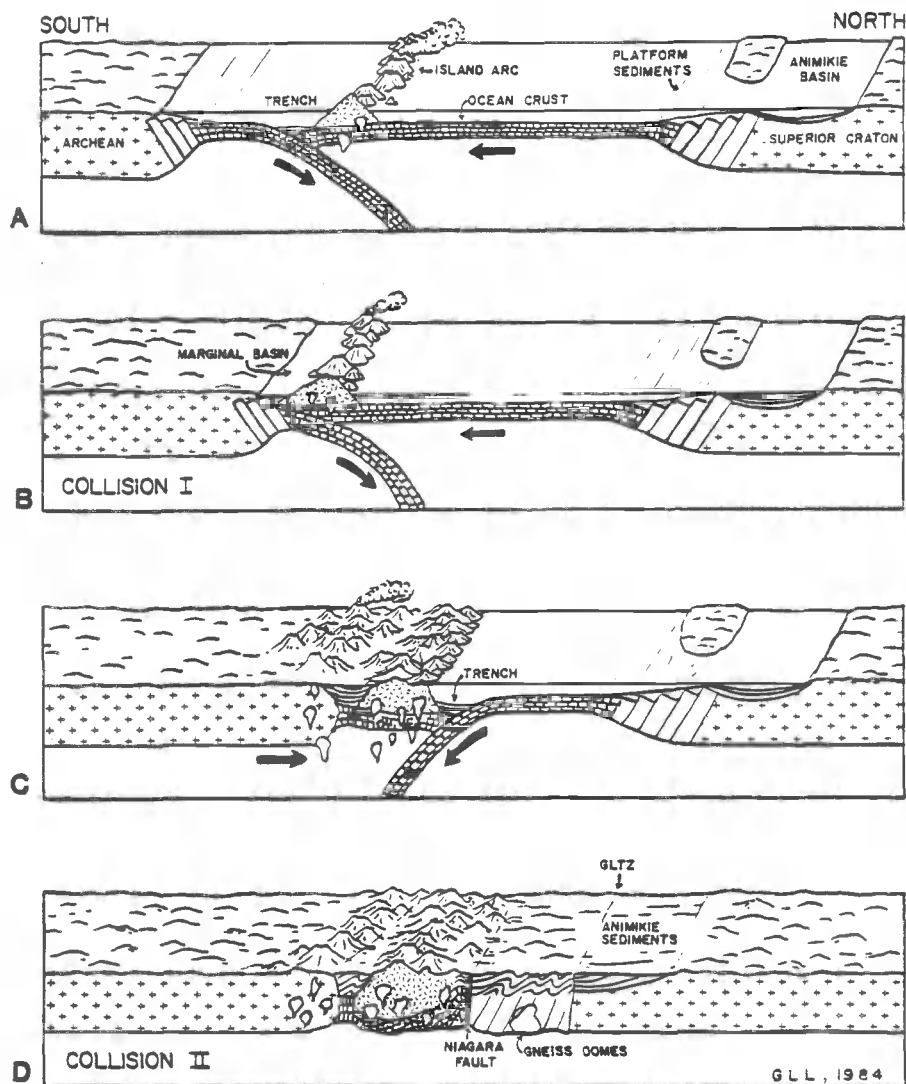


Figure 2. Block diagrams illustrating the possible sequence of events in the early Proterozoic in Wisconsin.

- A. Development of an island arc over a north-dipping subduction zone offshore from the Superior Craton. Platform sediments formed on the passive margin of the Superior Craton. (Volcanic succession I.)
- B. Archean craton from the south collides with the island arc.
- C. Continent-margin igneous activity over a south-dipping subduction zone as the ocean basin on the north side of the island arc closes. (Volcanic succession II, greenschist facies rocks.)
- D. Collision of the island arc with the platform sediments and the Superior Craton. (Volcanic succession III - caldera-type volcanics in central Wisconsin.)

Geology of the Lone Mountain Gold Prospect, Northeast Nevada

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The Lone Mountain gold prospect is located in the Independence Range of northeastern Nevada. It lies within the Arsenical Gold Belt of epithermal deposits along with the Carlin, Getchell and FMC-Freeport mines (Fig. 1).

Rock exposed on Lone Mountain include: Ordovician allocthonous eugeosynclinal cherts and shales (western facies rocks); Silurian-Devonian autocthonous miogeosynclinal Roberts Mountains Formation limestones (eastern facies rocks); and various Tertiary intrusive and volcanic rocks, including the Nannies' Peak quartz monzonite which forms the crest of Lone Mountain.

A variety of siliceous rocks termed "jasperoids" occur within the limestone beds of the Roberts Mountains Formation on Lone Mountain and are associated with anomalous concentrations of gold, mercury, arsenic, antimony, and thallium. Field and laboratory investigation by the authors identified four types of jasperoids: 1) sandy jasperoids, which are cavity filling rocks that consist primarily of quartz sand grains; 2) fine-grained jasperoids, which are cavity filling rocks that are laminated and consist primarily of silt- and clay-size quartz grains; 3) silicified limestone jasperoids, which are limestones in which calcite has been replaced by quartz; and, 4) jasperoid breccias, which are cavity filling breccias that consist of fragments of any, or all of the previously-listed rock types. Sandy jasperoids, fine-grained jasperoids, and jasperoid breccias (the "cavity filling jasperoids") are detrital rocks that occupy complex networks of solution cavities and fractures in the coarse-grained limestone of the Roberts Mountains Formation. They occur as isolated and/or interconnected bodies as much as one thousand feet in length. Silicified limestone jasperoids occur as irregularly shaped zones up to thirty feet in length which are adjacent to cavity filling jasperoids.

The solution cavities which host the cavity filling jasperoids were formed and filled by karst processes after the emplacement of the Nannies' Peak Intrusive. The detrital quartz grains in the karst cavities were derived from the coarse-grained limestones of the Roberts Mountains Formation.

Multiple waves of epithermal fluids, related to the late Tertiary to Recent igneous system on Lone Mountain, moved preferentially through the filled solution cavities and other permeable zones in the Silurian-Devonian Roberts Mountains Formation. These fluids deposited early and late calcite in veins, silicified the cavity filling jasperoids and portions of the Roberts Mountains Formation limestone, and deposited finely disseminated gold, plus mercury, arsenic, antimony, and thallium.

We conclude from a review of the chronology of geologic events that have affected Lone Mountain that the location and distribution of epithermal gold, arsenic, antimony, thallium and accompanying

silicification are controlled more by the "plumbing system" than by the rocks in which they are found. The epithermal fluids which have altered and mineralized the rocks of Lone Mountain are related to late Tertiary to Recent igneous activity; however, the mineralized rocks are lower Paleozoic. This conclusion recognizing the importance of the "plumbing system" rather than host rocks has serious implications when exploring for disseminated gold whether in Nevada or the Precambrian volcanic-sedimentary terranes of the Lake Superior region.

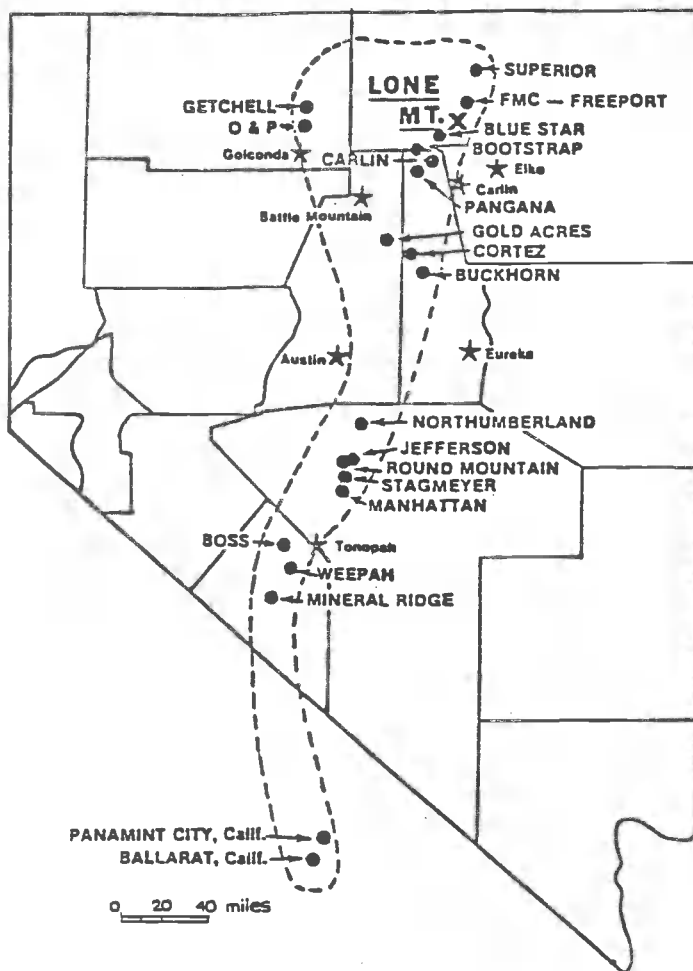


Figure 1. Arsenical gold belt of Nevada
(Modified from Joralemon, 1978)

- x Lone Mountain prospect
- Gold deposits
- * Communities

Geology of the Groveland Mine, Felch District, Michigan

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The Groveland iron mine is located within the Felch Trough in Central Dickinson County, Michigan. The Middle Proterozoic rocks exposed in the mine are the Randville Dolomite, the Felch Formation, the Vulcan Iron Formation, and the "northside schist." A gabbro sill intrudes the northside schist, and two nearly vertical granite dikes trending north-south cut the entire sequence. These rocks were folded, faulted, and metamorphosed to the amphibolite facies during the Penokean Orogeny.

The metasedimentary rocks exposed in the mine strike generally east-west and dip steeply to the north. James et al. (1961) and Cumberlidge & Stone (1964) concluded that the Vulcan Iron Formation and surrounding rocks form a tight, asymmetrical syncline whose axial plane dips to the north at approximately 60°. More recently (1978) the Hanna Mining Company staff proposed that the rocks form a faulted monocline dipping steeply to the north and that the "northside schist" is not correlative to the Felch Formation.

Our work in progress (BGSU, 1982-84) suggests a much more complex array of faults and folds to account for the repetition of beds and the apparent doubling in thickness of the iron formation at the mine site.

Several faults are clearly visible in the mine. The east end of the pit is bounded by a major fault which strikes NW-SE and dips steeply to the SW. At this fault the iron formation terminates abruptly against Randville Dolomite. Also, a set of faults strike E-W parallel to the iron formation and dip approximately vertically. These faults offset the granite dikes and appear to have right lateral and normal components.

A complex series of nearly isoclinal folds is clearly exposed in an outcrop of Randville Dolomite in the southwest wall of the pit. This pattern of isoclinal folding may be characteristic of the deformation of all the metasedimentary units in the Felch Trough. More work is currently in progress at the mine and elsewhere in the Felch Trough in order to better define the overall structure.

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Potassium Metasomatism of Trondhjemite Migmatite Wallrock,
Vermilion Complex, Northern Minnesota

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Extensive collecting of migmatite wallrock in the southeastern contact zone of the Vermilion Batholith has been carried out over the past six years by the Beloit College Department of Geology. Potash feldspar distribution was studied in specimens from the Fourtown Lake, Friday Bay, Jackfish Lake, and Basswood Lake West quadrangles through feldspar staining, cathodoluminescence, and petrographic techniques. The specimens investigated were collected from the three major map units of the study area. Granite-rich migmatite (Mg) and biotite schist-rich migmatite (Mb) differ only in percentage of granitic material (leucosome) relative to biotite schist (paleosome). Leucocratic biotite adamellite (La) is the rock type of the Vermilion batholith.

The paleosome and selvage layers of the migmatites are devoid of potash feldspar. The leucosomes are of two different rock types, trondhjemite and adamellite, depending on amount of potash feldspar present. Leucosome composition is illustrated in Fig. 1. The distribution of the potash feldspar is very selective and of a non-gradational nature. Textural relationships indicate replacement of plagioclase by potash feldspar. Quartz in the leucosomes is late and replaces the feldspars. In the field, the pink adamellite can be seen cross cutting and invading the light grey trondhjemite layers and veins.

Specimens from the area mapped as the southeastern border of the Vermilion batholith (La) show some compositional layering with respect to potash feldspar, although the potash feldspar distribution is much more uniform than in the leucosomes of the migmatites. Textural relationships indicate replacement of plagioclase by potash feldspar.

Field and laboratory evidence suggests that the original leucosome of the migmatite wallrock of the Vermilion complex was all trondhjemitic. Later, through potassium metasomatism, much of the trondhjemitic leucosome was converted to adamellite. The origin of some of the quartz in these migmatites may be related to the origin of the metasomatic potash feldspar. The rocks mapped as the southeastern border of the Vermilion batholith show the same metasomatic relationships as the migmatites, but on a more uniform basis. It is possible that the Vermilion batholith itself may have been a tonalitic or trondhjemitic intrusion which was later transformed to adamellite through extensive potassium metasomatism. If this

is not the case, than the "batholith rocks" (La) examined in this study are not true batholith rocks but highly metasomatised (granitized) wall rock.

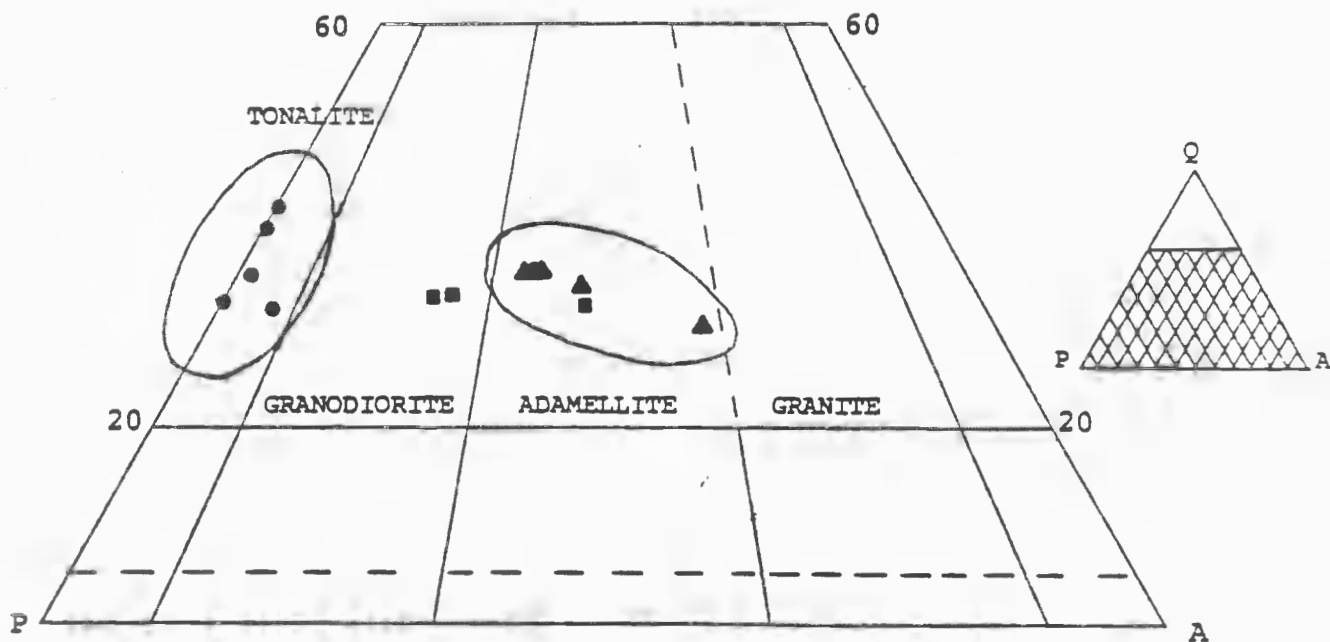


Figure 1. Plot of the relative percentages of modal quartz (Q), alkali feldspar (A), and plagioclase (P) for the migmatite leucosomes and batholith rocks (La). Percentages are plotted on an IUGS classification triangle.

- - Trondhjemite leucosome
- ▲ - Adamellite leucosome
- - Batholith rocks

Late Archean Metamorphic Conditions
at
Granite Falls, Minnesota

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A detailed geothermometric and barometric investigation has been completed for Archean granulite facies gneisses at Granite Falls, Mn. Garnetiferous and biotite-bearing variants of the hornblende-pyroxene gneiss and cordierite- and orthopyroxene-bearing variants of the garnet-biotite gneiss of Himmelberg (1968) contain a number of assemblages for which accurate thermobarometric calibrations have recently been calibrated.

The composition of cordierite ($Mg/(Mg+Fe)=.80$) which occurs locally in garnet-biotite gneiss requires metamorphic conditions of approximately 710°C , 5.6kb, and $X(\text{H}_2\text{O})=.30$ (Lee and Holdaway, 1977). Temperatures of 655°C and 664°C have been obtained for coexisting garnet and clinopyroxene (Ellis and Green, 1979) and magnetite and ilmenite (Spencer and Lindsley, 1981), in garnetiferous hornblende-pyroxene gneiss. Coexisting orthopyroxene and clinopyroxene in biotite-pyroxene gneiss yield temperatures for clinopyroxene consistently around 675°C (Lindsley, 1983), whereas temperatures for orthopyroxene are less reliable, ranging from 500°C to 600°C . Garnet, cordierite, and biotite in garnet-biotite gneiss exhibit compositional zoning due to partial re-equilibration during cooling. The rims of adjacent garnet and cordierite (Thompson, 1976) and garnet and biotite (Thompson, 1976, Ferry and Spear, 1978) yield temperatures of 620°C - 630°C , whereas cores of one garnet-cordierite pair yield a temperature of 660°C .

Pressure estimates based on the assemblage orthopyroxene-garnet-plagioclase-quartz in garnetiferous hornblende-pyroxene gneiss (Bohlen and others, 1983) and garnet-biotite gneiss (Newton and Perkins, 1982) lie in the range 4.7 to 5.3kb. Application of the orthopyroxene barometer, based on the Al-content of orthopyroxene in equilibrium with garnet (Harley and Green, 1982) is prohibited for these gneisses because of inappropriate compositions.

A late Archean metamorphic geotherm of $36^{\circ}\text{C}/\text{km}$ has been established for the gneisses at Granite Falls, using the most reliable estimates of temperature, 665°C , based on magnetite-ilmenite, garnet-clinopyroxene, and pyroxene thermometry, and pressure, 5.0kb, based on orthopyroxene-garnet-plagioclase-quartz equilibria.

Compared to other granulite terranes, the metamorphic conditions at Granite Falls were relatively low in terms of temperature and pressure. The calculated metamorphic geotherm is not significantly different from other Phanerozoic andalusite- and kyanite-sillimanite facies series terranes. Granulite facies conditions may have been caused by the same thermal regime that resulted in the widespread late Archean magmatism in the southern Canadian Shield.

Early Proterozoic Geology of East-Central Minnesota - A Review and Reappraisal

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Investigations by the Minnesota Geological Survey in east-central Minnesota over the past 15 years have shown that the northwest segment of the Animikie basin developed during early Proterozoic time over and approximately parallel to the Great Lakes tectonic zone. Although the tectonic zone is a major Archean suture that clearly remained an important structural element during the early Proterozoic evolution of the Animikie basin, there is no evidence that the zone ever defined a Proterozoic continental margin in Minnesota.

Goldich and his colleagues in 1961 were the first to conclude that the Animikie basin evolved through an extensional stage, during which stratified rocks were deposited, and a subsequent compressional stage, termed the Penokean orogeny. The Penokean deformation was viewed by Goldich either to have terminated sedimentation, or to have followed shortly after sedimentation ceased. The Penokean orogen can be divided into two broad longitudinal zones on the basis of contrasting styles of deformation and grades of metamorphism -- a northern stable zone and a southern deformed zone termed the Penokean foldbelt. The tectonic front separating the two zones coincides with the inferred northern edge of the Great Lakes tectonic zone in the Archean basement, and is marked by the northern limit of a penetrative cleavage. Little deformation and metamorphism occurred to the north of the front, whereas south of it some of the rocks have been multiply folded and metamorphosed. Intrusive rocks within the orogen include small to moderate-size plutons of late-tectonic granodiorite and sodic granite, and large plutons of post-tectonic potassic granite. Dikes, sills, and small bodies of gabbroic, dioritic and lamprophyric affinity also are present and were emplaced at different times throughout the evolution of the orogen.

Depositional patterns reflect contrasting tectonic conditions in the northern and southern segments of the Animikie basin. A relatively thin succession (2-3 km) of predominantly sedimentary rocks (Animikie Group) was deposited north of the tectonic front, whereas a much thicker succession (>6 km) of sedimentary and volcanic rocks (Animikie and Mille Lacs Groups) was deposited south of the front. The depositional history of these rocks can be divided into five phases. During the first two phases, quartz-rich rocks derived from source areas both north and south of the basin were deposited. In addition, the southern part of the basin received a substantial thickness of basic volcanic rocks, carbonaceous lutite, and iron-formation. During the third phase, a variety of iron-formation types were precipitated on a southward-facing shelf, whereas the fourth phase represents a transitional succession of carbonaceous lutite that formed as the shelf foundered into deep water. During the last phase a thick, southward-facing, flysch-like clastic wedge was deposited by southward-flowing turbidity currents.

The geologic history outlined above is broadly comparable with that of the Marquette Range Supergroup in the southeastern segment of the Animikie basin in northern Wisconsin and adjoining Michigan. Both sequences have sedimentological attributes similar to those of Phanerozoic geosynclines and both can be best explained by rifting processes akin to those proposed to explain the opening of a Phanerozoic protoceanic basin. However the general absence of structural and lithologic evidence for a cryptic suture, and the lack of voluminous early Proterozoic volcanic rocks like those in the Ladysmith-Rhinelander volcanic belt of northern Wisconsin raise serious problems for paleogeographic reconstructions of central Minnesota that involve a consuming continental margin. However similar volcanic rocks may occur in the subsurface of Iowa and southern Minnesota, and their absence from central Minnesota may be explainable by a major left-lateral displacement of early Proterozoic age, perhaps concealed by the middle Proterozoic Midcontinent rift system. If such a discontinuity could be demonstrated it would imply that the volcanic rocks of north-central Wisconsin and the rocks of the Animikie basin proper are separate and temporally discrete packages.

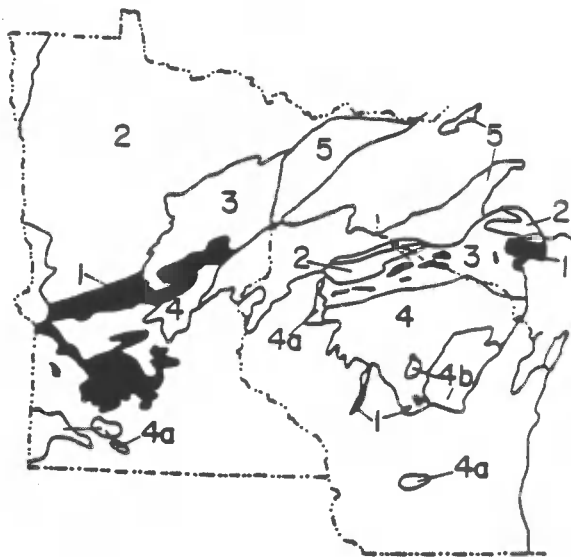
Correlations and paleogeographic reconstructions also are hindered by an incomplete understanding of the deformational history of the Penokean foldbelt. For example T.B. Holst has shown that the southern part of the Penokean foldbelt in east-central Minnesota is characterized by an older "nappe-like" structural geometry and a superposed younger "upright" structural geometry, whereas only the "upright" geometry occurs to the north. The inferred boundary between them appears to separate rocks of contrasting metamorphic grade and may also correspond to a mappable break in aeromagnetic data. Holst tentatively concluded that the structural break was the nose of a major nappe-like structure formed during the Penokean orogeny. Alternatively, we suggest that the structural break could be the trace of a folded unconformity beneath the Thomson Formation. The possible presence in east-central Minnesota of two early Proterozoic successions separated by a major period of folding and metamorphism is admittedly speculative. Nonetheless it is now becoming obvious that the evolution of the Penokean foldbelt was episodic with alternating periods of compression and periods of extension and sedimentation. Therefore we suggest that the Penokean orogeny should no longer be viewed as a single event sharply marked in time.

Metallogeny of the Lake Superior Precambrian

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For purposes of metallogenic analysis, the Lake Superior Precambrian region can be divided into five tectono-stratigraphic terranes: (1) an Archean gneiss terrane older than 3.0 Ga, and (2) an Archean greenstone-granite terrane about 2.7 Ga, the two joined together in late Archean time; (3) an epicratonic cover on this Archean basement of an Early Proterozoic miogeoclinal assemblage and associated epicratonic rocks (the Penokean orogen of Minnesota-Michigan); (4) an Early Proterozoic eugeoclinal assemblage of intrusive and extrusive rocks with possible Archean basement (Wisconsin magmatic terrane) that has a cover of intracratonic, an-orogenic continental rhyolites, quartzites and associated granitic rocks (Baraboo sequence-4a) and is intruded at 1.5 Ga by an-orogenic alkalic granites (Wolf River sequence-4b); and (5) a Middle Proterozoic (1.1 Ga) rift assemblage (Keweenaw terrane--Midcontinent rift system). The Early Proterozoic eugeoclinal assemblage was attached to the North American craton about 1.85 Ga. The Lake Superior craton has been tectonically stable since the Keweenaw.



Numbers refer to terranes. See text.

The potential of the Archean terrane is limited to minor iron, gold, base metals(?), and quality dimension stone. Greatest mineral production and future potential is from the Proterozoic terrane.

The Penokean orogen contains the major iron-formations in a basin in which the sedimentary fill thickens southward from about 2,000 m in the Mesabi and Gogebic iron ranges on the northwest to about 5,500 m and 8,000 m in the Cuyuna and Menominee ranges, respectively. The thinner sequences contain no volcanic rocks, whereas the thicker and sedimentologically more complex miogeoclinal sequences south of the Mesabi and east of the Gogebic ranges contain many locally thick piles of marine tholeiitic lavas. Other metallogenic settings on the Penokean orogen are related to Proterozoic unconformities and subsequent epigenetic environments.

The Wisconsin magmatic terrane, on the other hand, contains mineral occurrences related to both magmatism and high temperature hydrothermal deposition. Most important are the massive sulfide deposits along a belt of felsic to intermediate calc-alkaline volcanic rocks. These

bodies exhibit many similarities to the Noranda- and Kuroko-type ores including general form, mineral zoning, disseminated footwall mineralization, and mineralization succeeded by a period of sedimentation. However, there are also several differences. There is a general lack of well developed magnetic anomalies over the deposits indicating the absence of diagenetic magnetite and pyrrhotite; the overlying sediment is more a clastic than a chert; and although the major metal contents are similar to Archean deposits, precious metal abundances are only one-half that of Canadian deposits, but more similar to those in Canadian Proterozoic deposits.

Anorogenic sequences include the Baraboo, Wolf River and Keweenaw sequences. In the Baraboo sequence the only occurrences of metallogenic interest or curiosity are the speculative unconformity-related occurrences of uranium and the minor, thin iron-formations. The Wolf River sequence contains minor occurrences of U-Th, REE, and possibly Sn-W. By contrast, the Keweenaw is a copper-rich province and contains major stratiform deposits of native copper in basalts and interflow conglomerates, stratiform deposits of copper sulfide in black shale, as well as Cu-Ni-(Co) concentrations in the basal part of the Duluth Complex, and Ti-V concentrations in melanogabbros of the Duluth Complex and Mellen Intrusive.

Some deposits are younger than their host rocks so that, in detail, a tectono-stratigraphic framework may contain some flaws. It is also clear that in some instances, younger epigenetic processes have modified earlier syngenetic or coeval mineral concentrations. In the case of iron ores, it is these later processes that have converted uneconomic material into commercially extractable ores.

This study was undertaken to set the mineral deposits in this region into a metallogenic framework for the Lake Superior Precambrian Volume of the Decade of North American Geology (DNAG). The DNAG text will include abbreviated descriptions of the more important mineral deposit types with data on past or current production (Keweenaw copper; Lake Superior iron ore) or on reserves or resources Wisconsin zinc-copper; Minnesota Cu-Ni). Further, the tectono-stratigraphic framework allows us to propose metallogenic settings for still other kinds of mineral commodities, including Sn-W, diamonds, petroleum, and Skellefte- and Noril'sk-type nickel occurrences.

MICHIGAN-MINNESOTA ARCHEAN TERRANES						PENOEKAN OROGEN AND MIDCONTINENT RIFT SYSTEM						WISCONSIN MAGNETIC TERRANE, ANOROGENIC						MAGMATIC BELT, AND CRATONIC SEDIMENTARY COVER					
		LITHOLOGY	TECTONIC SETTING	MINERAL POTENTIAL	EXAMPLE/AREA	REFERENCE			LITHOLOGY	TECTONIC SETTING	MINERAL POTENTIAL	EXAMPLE	REFERENCE			LITHOLOGY	TECTONIC SETTING	MINERAL POTENTIAL	EXAMPLE	REFERENCE			
		pre-Late Cretaceous	paleoregoliths, paleosols	cratonic	soft iron ores	west Mesabi Range, Mn	44,53,90																
		post-Ordovician	kimberlite	cratonic																			
		pre-Late Cambrian	paleoregoliths, paleosols	cratonic	soft iron ores	Iron River, Mi	28			pre-Late Cambrian	paleoregoliths, pal	cratonic	supergene Cu	Flambeau, Wi	47								
Midcontinent Rift System (Keweenaw)	1.1 Ma	sandstone & shale	late-rift & post-rift	unconformity-type U dimension sandstone strata bound Cu-sulfide fissure veins(Cu, Ni, Co, Ag)	Big Erics, Mi Bayfield Peninsula, Wi White Pine, Mi Cook Co., Mn, Douglas Co., Wi Mt. Bohemia, Mi	30,31 13,78 93 22,58 63																	
	Middle Proterozoic	dikes & sills		diabase contact zones (U) feldspar anorthosite hosted Ti-V layered chromite taconite gabbro hosted Cu-Ni-(Co)	Theno Point-type, Ont Silver Bay, Mi Round Lake, Wi Crystal Lake, Ont Hoyt Lakes, Mn Minnamax, Mn Mineral Lake, Wi Grand View, Wi	30,31 87 25,26,76 21 42,43,53 83,84,87 3 1,32,33			1.1(?) Middle Proterozoic	dikes													
		gabbro intrusions---contact metamorphism																					
		rhyolite intrusions conglomerate tholeiitic basalt & interflow conglomerate tholeiitic basalt quartzite -----unconformity-----	cratonic	disseminated copper stratabound native Cu trap rock	Bear Lake, Mi Keweenaw Peninsula, Mi Dresser, Wi	91 46																	
	1.1-1.34																						
Baraboo Sequence	1.63	-----regional thermal metamorphism-----																					
	late Early Proterozoic	quartzite	cratonic clastic basin	catlinite	Pipestone Mn	55			1.48 Middle Proterozoic	rapakivi granite, a site, gabbro syenite	stable craton anorogenic	crushed stone (rapakivi) feldspar U-Th, Be REE-Th-U, Mo,F	Nine Mile Granite, Wi Tigerton Anorthosite, Wi Split Rock, Wi Stettin Complex, Wi Wausau Syenite, Wi	2,35 88 30,31 35,73 35,73									
Penokean Orogen	1.76	-----unconformity-----																					
	Early Proterozoic	-----regional thermal metamorphism----- alkalic intrusions	late orogenic	iron formation-U unconformity vein breccia (metamorphosed iron formatic kyanite)	Crystal Falls, Mi Exeland, Wi Republic, Marquette Range, Mi Bear River, Wi	20,30 65 4,19,34,59																	
		slate-graywacke		graphite, anthracite		72,89																	
		-----weathering----- iron formation		hard iron formation Mn iron formation Po-Py iron formation iron formation	Michigamme, Mi Cuyuna Range, Mn Aitkin, Co, Mn Mesabi Range, Mn	53 54 52 43																	
	tholeiitic volcanic rocks, dikes, sills orthoquartzite	passive margin ensialic	U-phosphorite	East-central Minnesota	15,50																		
	1.9-2.2	dolomite tillite -----unconformity-----																					
Minnesota-Michigan Archean Terrane	2.6-2.8	Late Archean tonalite-granite batholiths tholeiitic volcanic rocks exhalative iron formation ultramafic intrusions	cratonization island arc	Cu-Zn massive sulfide iron formation gold veins	Koochiching Co., Mn Soudan, Mn Ropes, Mi	60,69 40 10,64																	
	3.05	Middle Archean high-grade metamorphism pegmatitic granite & quartz monzonite granite-tonalite felsic to amphibolitic gneisses		pegmatites dimension stone					3.0 Middle to Late Archean	granite gneiss		dimension stone	Linwood, Wi	39									
	3.3-3.5																						
Relationship uncertain																							
M. G. Mudrey, Jr. and J. Kalliokoski, 1984, Metallogeny of the Lake Superior Precambrian: 30th Institute on Lake Superior Geology (Wausau, Wisconsin)																							

Metamorphic Conditions and Evolution of a Supracrustal Sequence
Intruded by the Dunbar Genesis,
Florence and Marinette Counties, Northeastern Wisconsin

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A suite of lower Proterozoic graphitic-sulfidic metasediments and intercalated mafic to intermediate volcanics and volcanoclastics from Florence and Marinette Counties are described. The supracrustal sequence (Quinessic Fm of Dutton, 1971) is characterized by prograde metamorphic assemblages including: biotite-garnet-plagioclase-quartz $\pm$ cordierite in metasediments, garnet amphibolites, and diopside-tremolite marbles. A late stage retrograde overprint is present in most samples studied to date. The most prevalent alteration includes: cordierite $\rightarrow$ pinite + sericite, garnet $\rightarrow$ biotite + chlorite, and hornblende $\rightarrow$ actinolite + biotite $\pm$ chlorite. The local concentration of S in several horizons has led to the development of pyrite $\pm$ pyrrhotite with a loss of Fe from the silicate phases. The supracrustal sequence is intruded by pegmatites and quartz-tourmaline veins analogous to those found within the Dunbar Gneiss Complex.

The prograde assemblage suggests peak metamorphic conditions in the range 500-575°C at low to intermediate lithostatic pressure. The abundance of graphite, calcite, and pyrite $\pm$ pyrrhotite indicate that $P_{H_2O} < P_{total}$ and that CO_2 and H_2S were (at least on a local scale) major fluid components.

Petrographic observations show an S_1 foliation developed parallel to S_0 bedding planes. A weakly developed S_2 foliation developed during retrograde metamorphism and is defined by second generation biotite. The S_2 foliation is inclined to S_1 by up to 90°. Garnets in the graphitic-sulfidic pelites contain abundant oriented quartz inclusions producing a pseudo-tetragonal sector pattern. Occasional zoned plagioclase phenocrysts are preserved in the amphibolites.

The intruded Dunbar Gneiss ranges in composition from granite-granodiorite to biotite tonalite and locally contains abundant mafic inclusions. In many outcrops, the well foliated gneiss grades into migmatites. Multiple generations of pegmatite cut the Dunbar Gneiss and are highly deformed themselves. The gneiss displays a similar sequence of fabric development as that shown by the supracrustals (Sims, 1984, personal communication).

Most of the samples discussed in this study were obtained from a series of diamond drill cores from the Bass Lake area, Florence County. These samples were made available by Kerr-McGee Corporation in Marquette, Michigan. Their cooperation is gratefully acknowledged.

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

MDB - a Metamorphic Mineral Assemblage DataBase for the
Precambrian of the Lake Superior District

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The Metamorphic DataBase (MDB) is a database established at UW-Parkside designed to facilitate the compilation, retrieval and subsequent plotting of metamorphic mineral assemblage data for the Precambrian of the Lake Superior District. MDB consists of two parallel files, one LLOC storing location data and the other MLOC which contains a list of minerals present. The Relational Information Management System (RIM) supported by the IBM system at UW-P is used to select user specified 'critical' mineral assemblages and at the same time retrieve the corresponding LLOC component. The selected assemblages and corresponding location data are stored in an output file which may be printed and used as input to a flatbed plotter to produce maps showing the areal distribution of specified assemblages.

The relations between the variables in the LLOC file permit the generated output file to consist of data for a single county, quadrangle, state, or the entire Lake Superior District. A complete MDB entry consists of 2 components- a line of data for LLOC and a column of data for MLOC. LLOC input consists of an identification number, county, state, depth (0 = surface sample, > 0 = depth in a drill core), latitude and longitude (degrees, minutes, and seconds) age of metamorphism (if known), and a string termed ADINFO which indicates the type of work which has been done on the sample (thin section, microprobe data, bulk rock chemical data, and the contributor's name). The MLOC entry consists of a list of the (equilibrium) mineral assemblage observed in thin section and an identification number.

Once all data are entered into MDB, the user may select individual minerals or critical mineral pairs or assemblages and obtain a list of locations where the specified assemblage occurs. I am currently attempting to update the Metamorphic Mineral Assemblage Map for the Lake Superior District (Morey, 1978) incorporating new data and interpretations. It is anticipated that this material will be part of a contribution to the DNAG volume of the Precambrian of the Lake Superior District. A sample input form is included with this abstract, and I would welcome any and all contributions for inclusion in MDB.

Morey, G.B., Metamorphism in the Lake Superior region, U.S.A., and its relation to crustal evolution; in Metamorphism of the Canadian Shield, Geol. Surv. Can., Paper 78-10, p.283-314, 1978

Location file:

LLOC	County	State	Depth	Latitude ° ' "			Longitude ° ' "			Age	ADINFO
1	FLO	WI	140.0	45	46	37.5	88	22	5.2	PEN	TS PAN
2	FLO	WI	0.	45	49	50.5	88	17	5.2	PEN	TS PAN

Mineral file:

MLOC List of minerals present (no maximum) if the sample is polymetamorphic, it is recommended that separate identification codes and ages be assigned, along with separate mineral assemblage listings.

2 If MLOC and LLOC are integers and are equal for each sample in the file (MLOC=LLOC), MLOC and LLOC are assigned at the time the data are entered into MDB.

MLOC Minerals present

1	QTZ EPI TRE CAL
2	BIO GAR CTD CHL QTZ PLA

Basal Lower Proterozoic Glaciogenic Formations,
Marquette Supergroup, Upper Peninsula, Michigan

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Three basal Proterozoic formations in the Upper Peninsula of Michigan - the Reany Creek, Enchantment Lake, and Fern Creek - are interpreted to have had glacial origins. The strongest evidence for a glaciogenic history is oversized limestones (many of which are clearly dropstones) in laminated shale-siltstone beds that are associated with diamictites. They are interpreted to have been dropped into glaciomarine or glaciolacustrine environments from either icebergs or ice shelves. Other rock types within the three formations include graded & ungraded clast-supported conglomerate, sandstone, and siltstone. Most of the sand-sized grains in all the rock types are quartz. The Fern Creek and Enchantment Lake formations pass upward into formations of quartz-sand; the Reany Creek has a faulted upper contact. Microscopic till pellets are present in the dropstone units of the Reany Creek Formation.

The three formations, separated by as much as 80 km, unconformably overlie Archean basement. They may be correlative with each other, or the Reany Creek may be a younger but still lower Proterozoic unit. Several workers have proposed correlations of one or more of the units with the Gowganda Formation (interpreted to be of glacial origin) of the Huronian Supergroup, 200 km to the east in Ontario. The dropstone unit - diamictite association in each unit strengthens this correlation. Radiometric ages are not available in Michigan, but the Huronian Supergroup has been bracketed between 2500 and 2100 m.y. If any of the Michigan units prove to be younger than the Ontario glaciogenic formations, then another early Proterozoic glacial episode is indicated.

Stratigraphy of the Headway-Coulee Massive Sulfide
Prospect, Northern Onaman Lake Area, NW Ontario

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The Headway-Coulee massive sulfide prospect, situated within the Archean Wabigoon greenstone belt, is located within an intensely altered succession of mafic and felsic metavolcanic, and intrusive rocks. Detailed mapping and petrographic studies have shown that the volcanic succession can be divided into several distinct lithological units.

Pillowed, massive, and brecciated mafic flows form the base of the volcanic succession and are about 1.2 km thick. Flows vary from aphanitic to porphyritic, and have an amygdaloidal content ranging from 0 to 8 percent. The mafic flows are interfingering with and overlain by laminated to thickly bedded felsic hydrovolcanic rocks, which range from crystal-rich ash and lapilli- and block-size tuffs to associated debris flow deposits. These grade laterally into thin ash-sized deposits containing up to 15 percent fragments which are thought to represent reworked equivalents of the hydrovolcanic rocks. Overlying the hydrovolcanic units are spherulitic, massive to brecciated, quartz-feldspar porphyritic lava flows which may or may not be flow banded. The felsic unit is some 100 meters thick and extends along strike for approximately 4 km; it is overlain by pillowed to massive mafic lavas. An extensive polymictic debris flow deposit which contains clasts of mafic and felsic volcanic, granite, and iron formation is interfingering with the felsic horizon and is believed to have its origin to the southwest of the study area.

Crystal-rich laminated tuffs and thickly bedded fragmental rocks and associated debris flow deposits are believed to be the products of hydrovolcanic eruptions. Such eruptions form tuff cones with depositional products dependent upon water to magma ratios. Slumping and reworking would produce finely laminated distal equivalents of such deposits.

Alteration, Paragenesis and Age Associated with Native Copper
Mineralization of the Kearsarge Flow, Keweenaw Peninsula, Michigan

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The Portage Lake Volcanics consists of a thick sequence of Keweenawan tholeiitic flood basalts which hosts a dormant billion-dollar native copper district. The Kearsarge flow is a thick (60 km) ophitic to porphyritic basalt which contains a major ore-producing amygdaloidal flow top ranging from 0 to 10 m thick. Seven mines worked the Kearsarge amygdaloid along a strike distance of more than 12 km and produced over 2.3 billion lbs. of refined copper, the third largest lode in the district. Stoiber and Davidson (1959; Econ. Geol., v. 54, p. 1250-1460) documented an irregular but generally symmetric banding of secondary minerals within the flow top: chlorite and microcline were deposited earliest and farthest away from the zone of highest permeability, later epidote and quartz were confined to the most permeable horizons, and calcite filled the remaining pore space. Samples of Kearsarge flow top from poor-rock piles of the Wolverine Mine confirm this broad paragenesis on a single amygdale scale. Vesicle walls are lined with a thin layer of chlorite followed by a band of hematite-dusted microcline crystals which terminate in euhedral pyramids. Centers of amygdules are filled with a complex combination of bladed epidote with lesser amounts of fibrous prehnite, euhedral to anhedral quartz, native copper, and fine-grained masses of poorly-crystallized layer-silicates. Anhedral calcite fills remaining open pore space.

Rb-Sr isotopic data were obtained from a suite of secondary minerals from the Wolverine Mine. Early microcline and chlorite define an isochron with an age of $1,051 \pm 15$ Ma and an initial Sr ratio of 0.7145. The age of the Keweenaw lavas within the Lake Superior basin has been constrained by a variety of workers and is best estimated at about 1,110 Ma (Van Schmus and others, 1982; Geol. Soc. Amer. Memoir 156, p. 165-171). Thus, mineralization occurred about 50 Ma after the peak of igneous activity but probably during the later stages of sedimentary infilling of the rift basin. Later calcites and epidote contain virtually no Rb and have Sr ratios which cluster about a value of 0.704. They do not fit the microcline-chlorite isochron. The mineralizing fluids were apparently characterized by different early and late Sr isotopic compositions. We interpret this data as evidence for variable sized fluid convection during the evolution of the mineralization event.

Whole-rock major and trace element chemical compositions have been determined across a 19.5 m section of the Kearsarge flow. It is apparent that some elements such as P, Sc, Y, and Zr have remained largely immobile while others have experienced a dramatic redistribution during the metamorphic event. Mass balance calculations have been performed in an attempt to determine whether trace elements (K, Rb, Ca and Sr in particular) have behaved under open or closed redistribution conditions. These results will be presented.

Localized Accumulations of Upside-Down Trilobite Parts in Cavities within a Silurian Reef at Racine, Wisconsin

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Outcropping Silurian reef cores in Wisconsin and adjacent states are generally structureless masses of dolomite flanked by outward dipping, medium to thick beds that flatten and grade laterally into thinner bedded interreef dolomite. Large irregular cavities are common in many reef cores, and may be present in flank beds. Some reef cavities result from solution, but others containing concentrated accumulations of fossils were primary features formed during reef growth.

A partially quarried Middle Silurian (Niagaran) reef in Racine Dolomite at Quarry Lake Park, Racine, Wisconsin, exposes about 20 elongate bell-shaped or equant cavities ranging up to 8.5' wide, 3' high, and extending 6' inward from the face of the rock exposure. Many of the cavities couldn't be examined safely and several were nonfossiliferous. The base of three out of five cavities selected for detailed examination contained large numbers of nested masses of fossils dominated by inverted (concave-up) cephalons and pygidia of the trilobite Bumastus sp. Previous workers have suggested that similar accumulations might represent: (1) a protected living environment with reworking by scavengers, (2) a favored molting site, (3) wave and current accumulations behind obstacles or within depressions, or (4) settling of disarticulated fossils washed into natural cavities. It is also possible that unique and selective predation might account for the fossil deposits. The fact that most (all?) of the cavities within the reef core were once filled with clay adds to the enigmatic nature of these features.

Flume and settling experiments with chitinous carapaces and full dorsal exoskeletons of the horseshoe crab (Limulus sp.) disclose that only free-fall into a nonagitated cavity allows a high percentage of concave-up forms to accumulate. This documentation, plus the disarticulated and incomplete nature of Bumastus in association with lesser numbers of other fossil forms, suggests selective sorting of dead organisms by size and shape as they washed across the submerged reef flat before falling into depressions.

Although this project solved the mystery of upside-down trilobites, it failed to provide new insight into the origin and accumulation of clays within reef cavities.

Precambrian Evaporites: Preservation of Sulfate in
Quartz Pseudomorphs After Gypsum

E.C. PERRY, J. FENG, AND J. HEMZACEK (Northern Illinois University)

The average sulfur isotope composition of trace amounts of anhydrite preserved in the 2×10^9 year old Kona Dolomite from 3 distinct localities near Marquette, Michigan is 13.23 ‰ (CDT) with a total range of 1.2 ‰ . Much of this sulfate is preserved as microscopic inclusions in quartz pseudomorphs after gypsum, but at least one rock contains distinct sulfate crystals that dissolve on weathering leaving a pitted surface. Conspicuous pseudomorphs are associated with large, silicified stromatolites at a quarry 9 km southwest of the center of Marquette on highway 480. Other pseudomorphs from this quarry are replaced gypsum crystals up to about 3 cm long, which occur in maroon carbonate mudstone.

The significance of the discovery of sulfate in the Kona Dolomite is that marine evaporites, which contain a well documented record of the highly variable sulfur isotope composition of the Phanerozoic ocean, are almost nonexistent in the Precambrian except for a few sporadic occurrences that are 1.2×10^9 years old or younger. If sulfate is preserved in some of the numerous reported occurrences of Proterozoic and Archean sulfate pseudomorphs and if this sulfate has not suffered serious isotopic fractionation during diagenesis and metamorphism, it may be possible to extend the important sulfur isotope record of exogenic processes back to a time of low atmospheric oxygen.

Leaching experiments with sulfate from the Kona Dolomite indicate that the last few per cent of sulfate extracted is depleted in ^{34}S by about 1 ‰ . If this can be extrapolated to diagenetic and metamorphic processes responsible for replacement of evaporite minerals, it suggests that the original isotope composition may have been moderately higher in ^{34}S than the value we have measured. However, in the absence of a large and uniform external reservoir of sulfate, the extremely uniform sulfur isotope value that we have obtained, independent of sulfate concentration variations of 20X, is an encouraging indication that the original sulfur isotope composition of sulfate in the Kona Dolomite is preserved.

To test whether or not processes that encapsulate sulfate in silica produce significant sulfur isotope fractionation, we are collecting silicified material in Phanerozoic evaporites in order to compare the isotopic composition of trace sulfate inclusions with sulfate in the main evaporite minerals.

After finding preserved sulfate in the Kona Dolomite, we solicited the help of colleagues in assembling the most comprehensive possible collection of similar material from other localities. To be valuable, the sulfur isotope record of sea water sulfate must be reasonably complete. So far we have received quartz pseudomorphs after gypsum (or celestite) from Montana (1.2×10^9 years), Nabberu Basin, Australia (1.4 to 2×10^9 years), and Barberton, South Africa (3.4×10^9 years). We shall be grateful for material from other Precambrian or Phanerozoic localities of silicified evaporites or for information about such localities. It is our hope that such material, although inconspicuous, may be common and, ultimately, useful.

Stable Isotope Evidence of Metamorphism and Hydrothermal
Alteration, Negaunee Iron Formation, Michigan

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At equilibrium siderite, and particularly quartz, concentrate ^{18}O with respect to magnetite. This fractionation becomes less at high temperature so that during metamorphism a redistribution occurs, and magnetite gains ^{18}O from quartz and siderite. Because oxygen of carbonate and quartz in iron formation is quantitatively more abundant than oxygen of magnetite, $\delta^{18}\text{O}$ of magnetite in metamorphosed iron formation typically varies considerably as a function of bulk composition and metamorphic temperature. This pattern is not characteristic of low grade metamorphic zones of the Negaunee Iron Formation. Instead, the $\delta^{18}\text{O}$ of magnetite is almost constant throughout a given core whereas $\delta^{18}\text{O}$ of quartz and siderite varies considerably. We interpret this to indicate equilibration of the rocks with a metamorphic fluid. Over a large temperature range the oxygen isotope fractionation between magnetite and water is almost constant, while that between quartz or siderite and water varies by several per mil. Thus, a fluid dominated system would behave as the Negaunee Iron Formation does. Further evidence for hydrothermal fluid movement in this region is the disequilibrium reversal in quartz-siderite oxygen isotope fractionation that occurs near the base of several Negaunee Iron Formation cores.

Average temperature of metamorphism of zone I iron formation over a wide area, as determined by quartz-magnetite geothermometry, is $320 \pm 13^\circ\text{C}$. One of the cores characterized by this temperature contains a zone in which the following reaction is observed: siderite + minnesotaite = grunerite + CO_2 + H_2O . If a large part of zone I was balanced during metamorphism at temperatures and pressures near those that would release volatiles by such a reaction, rock permeability may have increased greatly at this locality opening conduits for fluids expelled from zones of higher grade metamorphism nearer the Republic trough. If this explanation is valid, the conduits, once formed, must have remained open to circulation of fluids after the peak temperature of metamorphism since both high and low isotope "temperatures" are recorded in the permeable zones.

Sills emplaced before the main regional metamorphic event occur in the upper parts of 2 cores that we have studied. These sills have produced distinctive contact metamorphic effects in underlying iron formation that are clearly preserved in the oxygen isotope composition of quartz, carbonate, and magnetite. High mineral isotope "temperatures" are recorded near the sills, but in the outer margins of the contact zones "temperatures" frozen in by the earlier metamorphism are distinctly lower than the temperature of regional metamorphism.

In at least one core an excellent correlation exists between amount of carbonate in a specimen and the $\delta^{13}\text{C}$ content of the carbonate. This relation holds over a range of $\delta^{13}\text{C}$ of approximately $-7^{\circ}/\text{oo}$ to $-11^{\circ}/\text{oo}$ and a carbonate content of 19 to 6%.

Middle Proterozoic Events in Northeast Wisconsin and
Adjacent Michigan as Defined by Rb-Sr Biotite Ages

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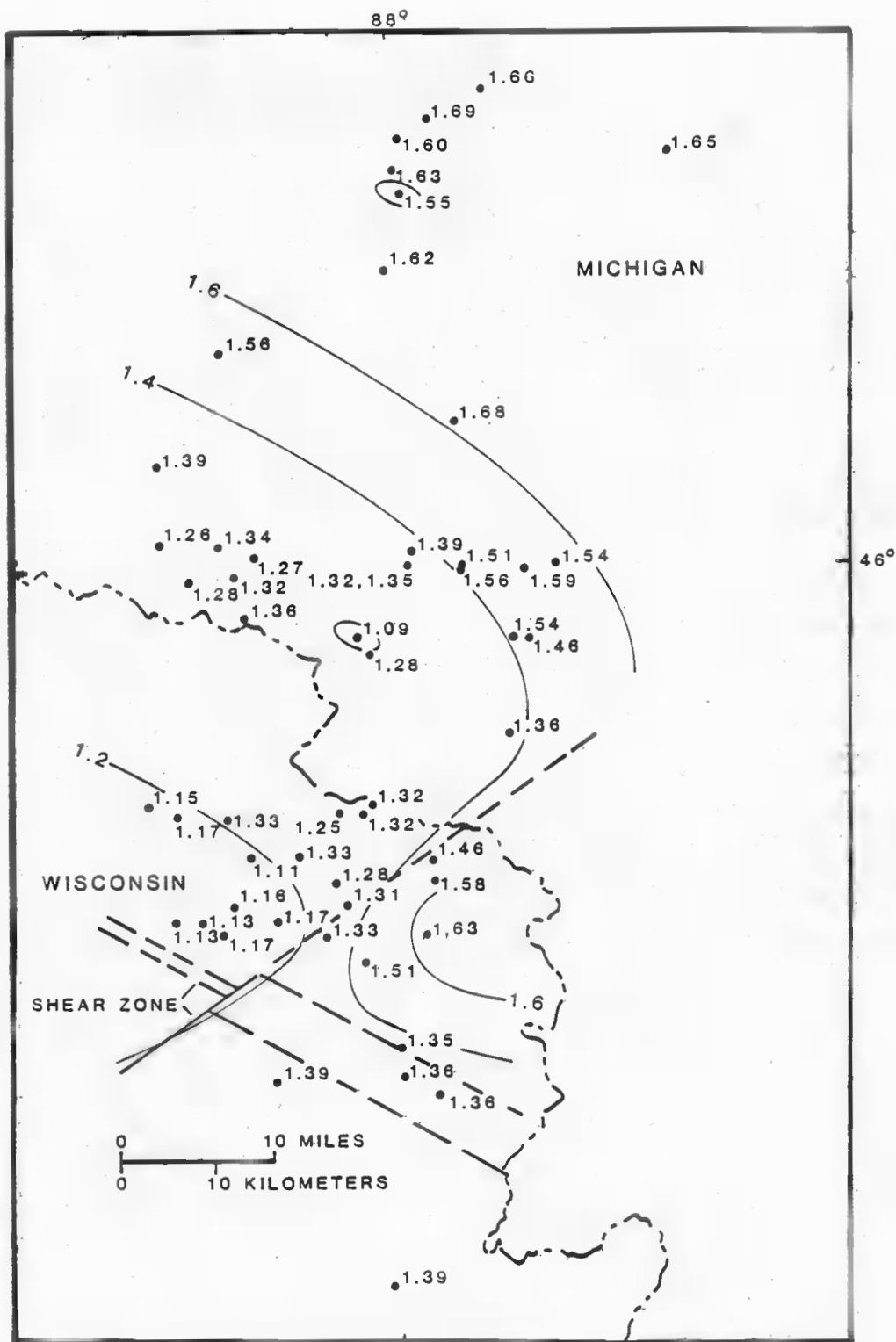
Systematic variations of Rb-Sr biotite ages for Early Proterozoic and Late Archean rocks in a transect extending 130 km from the Marquette trough in northern Michigan to northeastern Wisconsin record uplift events in the Middle Proterozoic (Figure). The biotite ages have a trimodal distribution with peaks at 1.58 ± 0.07 Ga (19 samples), 1.32 ± 0.04 Ga (26 samples), and 1.14 ± 0.03 Ga (9 samples). The 1.58-Ga peak is a composite containing the tightly clustered 1.63 ± 0.03 Ga ages for the southern complex in northern Michigan (Van Schmus and Woolsey, 1975) and slightly younger ages from areas to the south. The 1.32 Ga peak is defined by biotite ages in the Felch trough area (Aldrich and others, 1965) and in an area extending southward across the central part of the Dunbar gneiss dome in northeastern Wisconsin into the body of Athelstane Quartz Monzonite of Cain (1964) south of the dome. The western third of the dome is characterized by biotite ages that range from 1.11 to 1.17 Ga. This age zone merges abruptly to the east with the zone of intermediate ages, and the eastern part of the dome yields still older ages ranging from 1.46 to 1.63 Ga.

Resetting of the biotite-hosted Rb-Sr system could have resulted from thermal pulses related to igneous activity, recrystallization, or rapid uplift and cooling. At least two of the age peaks reflect complete resetting of the systems as suggested by the limited dispersion. The 1.63 ± 0.03 Ga biotite ages for Archean rocks of the southern complex have been correlated with an isotopically widely recognized but geologically cryptic event that has affected Precambrian rocks over much of Wisconsin (Van Schmus and Woolsey, 1975). The resetting of biotite ages in the western third of the Dunbar dome at 1.14 ± 0.03 Ga occurred contemporaneously with Keweenawan rifting and igneous activity. The coincidence of age discontinuities with northwest- and northeast-trending shear zones with vertical lineations (Figure) strongly suggests that differential vertical uplift was a causative factor in producing the age pattern. Rapid erosion, an inevitable corollary to rapid uplift, would have contributed Early Proterozoic detritus to Keweenawan sands.

The significance of the 1.32-Ga peak of biotite ages is less certain. Aldrich and others (1965) suggested a thermal event at this time, but did not elaborate on a possible cause. Possibly, the surface now characterized by the 1.32-Ga age group was uplifted and cooled during the Keweenawan from a depth at which the biotite systems were only partially reset.

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Rb-Sr biotite ages for Early Proterozoic and Late Archean rocks in northeast Wisconsin and adjacent Michigan. Data are from Aldrich and others (1965), Van Schmus and Woolsey (1975), and Peterman and Sims (unpublished). Note the close correspondence between age discontinuities and known and projected shear zones in northeast Wisconsin.

Crystallization Histories of Early Proterozoic Plutons from Northern Wisconsin

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A variety of Early Proterozoic plutons is exposed in northern Wisconsin. The plutons vary from gabbro to granite in composition, are mesozonal to hypabyssal in level of emplacement, and are syntectonic to posttectonic with respect to the Penokean orogeny. Recent field and petrographic work has established crystallization histories for the plutons and their aureoles, yielding important information on the petrologic evolution of this part of the crust in the Lake Superior region.

The plutons generally contain multiple generations of mineral assemblages, indicating complex crystallization histories. Posttectonic hypabyssal plutons contain relict euhedral or embayment textures representing crystallization from a silicate melt. Posttectonic epizonal plutons, pegmatites, and aplites exhibit textures which probably represent crystallization at or near the solidus. Syntectonic mesozonal plutons exhibit textures representing subsolidus crystallization. All of the plutons are overprinted by low-grade alteration products.

Previously unreported electron microprobe determinations of mineral compositions have been made for plagioclase and potassium feldspars, biotites, hornblendes, muscovites, garnets, and ilmenites. The mineral compositions allow estimations of the intensive parameters obtained during crystallization. Possible equilibria involving two feldspars and plagioclase-hornblende yield temperatures of 600-700°C for epizonal rocks and 400-600°C for mesozonal rocks.

Intrusion of Penokean and post-Penokean plutons occurred across batholithic dimensions in northern Wisconsin. Most of the Early Proterozoic metamorphism in the plutons and their aureoles probably occurred during intrusion and cooling of the plutons. According to this interpretation, Early Proterozoic metamorphism in northern Wisconsin was autometamorphism and contact metamorphism on a regional scale. These new data and interpretations place important constraints on models for the thermal evolution of this part of the crust.

Climatic Inferences of Iron-Formation from Associated
Diamictite facies sequences, Griqualand West Supergroup, South Africa

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Makganyene Diamictite underlies Ongeluk Lava (~2.2 Ga B.P.) at the base of the Postmasburg Group in Cape Province, South Africa. The diamictite is interpreted as glacial, which puts environmental constraints (e.g. temperature) on the formation of associated iron-formation sedimentary rocks.

In outcrops, diamictites are interstratified with conglomerate, sandstone, shale and pebbly mudstone. Direct evidence for the diamictites being glacial is two features of clasts: striated surfaces and faceted, flat-iron shapes. Most clasts are chert and striations are well retained on their surfaces. In some areas up to 10 percent of the clasts are striated (a high proportion in many Pleistocene glacial successions), and multiple striae orientations also occur. Some clasts (up to 2 percent locally) have a flat-iron form produced during basal transport in a glacier. The oligomictic clast composition, often cited as evidence against glaciation, can be explained as a source control. Underlying formations, which are probably the source, comprise iron-formation and carbonate rocks. Both carbonate and (iron-rich) shale clasts did not survive long transport by Pleistocene glaciers. Therefore, chert is the most likely component of glacial sediment in the Makganyene Diamictite. Glacial pavements have been noted by previous workers, however, none were found during this study. If many of the sequences are glacial (see below), then absence of a widespread pavement can be expected.

Other arguments are made for a glacial origin of the diamictite succession using lithofacies sequence analysis. Some of the associated sorted units are sheet-like sandstone bodies up to 12m thick. They are fine- to coarse-grained, occasionally pebbly or gritty, and are apparently structureless or exhibit horizontal lamination, medium-scale trough cross-bedding and channel forms. Basal conglomerates occur in the channel forms. A flaggy sandstone facies is common at the base of the succession. Asymmetrical and symmetrical rippled sandstone surfaces are draped with shale. The sandstones are interpreted as braided stream deposits probably in interaction with a shallow marine environment.

Other sorted facies are lensoid channels of structureless fine- to medium-grained sandstone within diamictite. The channels are stacked or isolated and include blocks of diamictite. The intertonguing of sandstone with diamictite indicates the genetic processes of both facies were episodic, or that the sandstone channels were limited in spatial position. This type of sequence has been described in Pleistocene subglacial lithofacies. The sequence may be

subaqueous where the diamictite is a compound para-till and the channels are subaqueous outwash. A submarine interpretation presents a difficulty because fluvial traction currents require extremely high sediment concentrations to be maintained at the base of a more dense sea water column.

One section exhibits facies associations typical of ice-proximal subaqueous environments. Diamictite grades into and out of pebbly mudstone, breccia/conglomerate beds, and thin sandstone beds. Another section comprises stacked debris-flow noses that have structureless diamictite cores and outer fissile zones exhibiting flow structure. Debris flows occur in terrestrial and submarine, glacial and non-glacial environments. Alluvial fan deposits have a geometry and facies associations that exclude them from consideration. Terrestrial ice-contact environments include resedimented deposits that cannot be excluded as a possible interpretation at some localities. Submarine debris flows are very rare in shallow water unless influenced by a glacier.

The succession is considered glacigenic. The glacier must have had a melting base because glacifluvial deposits are common. Frozen base glaciers like those in Antarctica today lack common fluvial deposits. The terrestrial glacier was probably an ice cap and/or valley glaciers based on, and south of the Ganyesa Dome. The glacier margin facing the epeiric sea was probably not an ice shelf because tidal ranges were sufficiently large to make an ice shelf unstable, even if the glacier was made of cold ice. Therefore, the glacier ended as a tidewater terminus. Furthermore, the presence of volcanic ash in some of the compound para-till indicates an open water iceberg zone environment close to shore. That necessarily excludes an ice shelf environment.

Deep drill cores show an intimate association of diamictite and chemical and clastic marine sedimentary rocks that include lean iron-formations. The Makganyene glacier, on a narrow shelf at the margin of the epeiric sea, probably enhanced upwelling as at present glacial margins. That upwelling may have enhanced chemical sediment deposition (iron-formation, chert, carbonate). The climate was not extreme (cf. Antarctica), but cool temperate (cf. Alaska) and that inference puts constraints on interpretations of oxygen isotope analyses of associated chemical sediments.

Magnetotelluric Profile of the Jacobsville Sandstone

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Seven magnetotelluric soundings were conducted along a NW-SE line across the Jacobsville Sandstone, between Keweenaw Bay and the Keweenaw fault in Michigan's Upper Peninsula. They have provided an estimate of the thickness and resistivity of the sandstone and the underlying basement.

The soundings were of a long enough period (up to 1818 seconds) to obtain data from layers at least several kilometers in depth. Initial interpretation is that the sandstone may be one to two kilometers thick, and that northwest of the Tapiola/Otter Lake area, the sandstone is underlain by the Portage Lake volcanics of a higher resistivity. To the southeast of this area the sandstone is underlain by a body of lower resistivity rock, perhaps Michigamme Slates which are known to outcrop at the head of Keweenaw Bay.

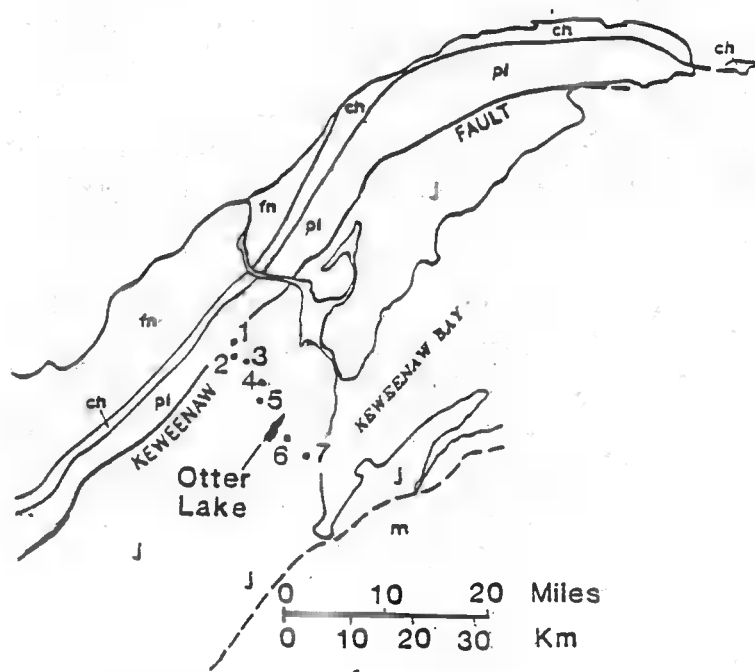


Figure 1. Location of soundings (stations 1-7), j, Jacobsville Sandstone; fn, Freda Sandstone and Nonesuch Shale; ch, Copper Harbor Conglomerate; pl, Portage Lake Lava Series; m, Michigamme Slate.

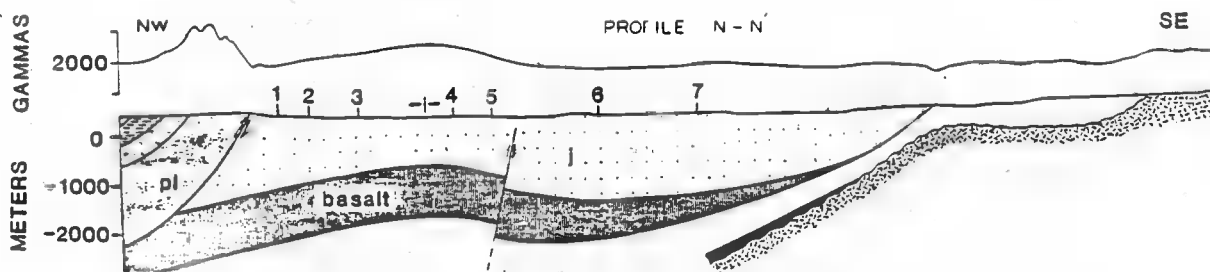
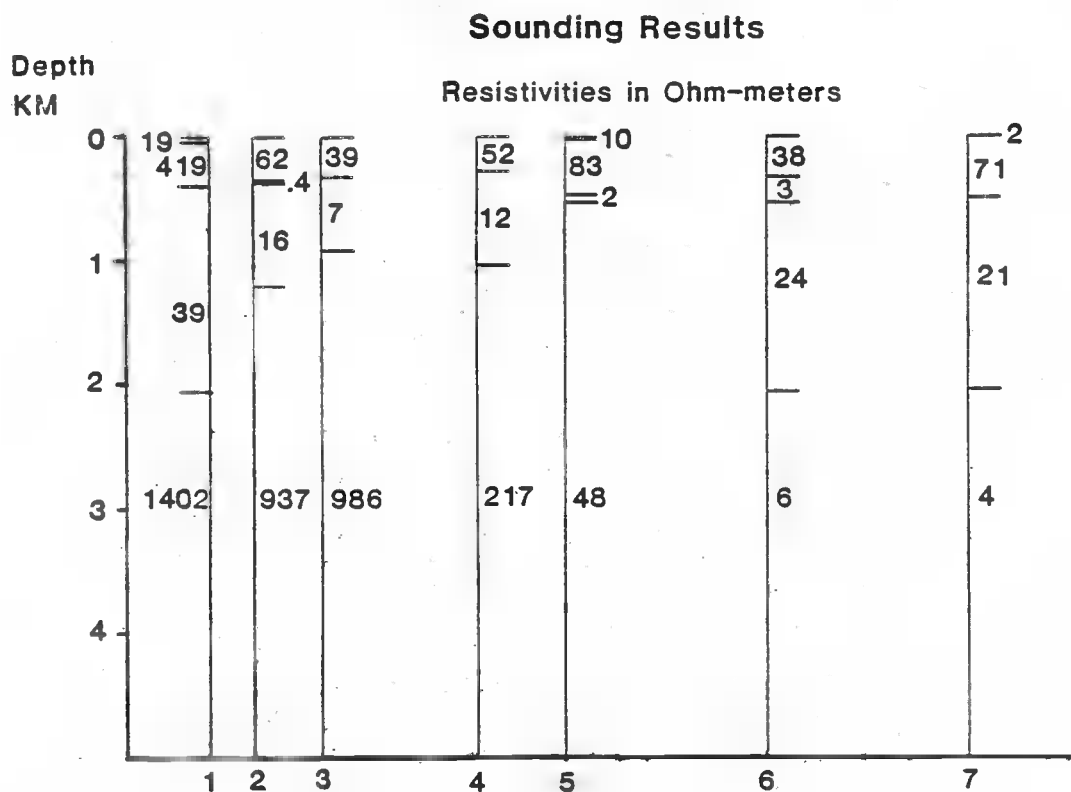


Figure 2. Sounding locations on a geologic cross section.
(Meshref and Hinze, 1970)

Pt and Ni Arsenide Minerals in the Duluth Complex

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Sperrylite (PtAs_2), maucherite (Ni_3As_2), and possibly niccolite (NiAs) have been identified in massive sulfide samples from the Duluth Complex. The identification was made in the course of a survey of three representative massive sulfide samples (Table 1) from the MINNAMAX Shaft (located about 8 km south of Babbitt, MN).

One sperrylite grain was found as a small, 2x5 micrometer, euhedral crystal in a larger, elongate grain of maucherite which in turn was embedded in an intergrowth of chalcopyrite-cubanite. Quantitative electron microprobe analyses indicate a deficiency of As for stoichiometric sperrylite (Table 2, 1 & 2). Minor elements total less than two wt. %. The sperrylite grain has a very complex internal structure which consists of an inclusion of a blade of graphite (?) and a complex myrmeketic intergrowth. This proved to be too fine-grained (2 micrometer wide blebs) for quantitative analysis, however, qualitative data indicate the possible presence of graphite, precious metal alloys, tellurides, and bismuth minerals. These phases are postulated on the basis of positive identification of C, Cu, Au, Te, Bi, and Pb peaks in x-ray dispersive (EDX) and scanning Auger microprobe spectra. Pd was identified in only one x-ray spectra in a myrmeketic bleb rich in Bi in the sperrylite grain.

Maucherite was found in all three samples studied. It is distinguished in reflected light microscopy from other sulfide and arsenide minerals by its white, high reflectivity and very faint pink tint. It was found in five polished sections as small blebs (10 micrometer) and as long needle-like stringers (0.01 to 1.5 mm long). It was found in all three major sulfide phases--pyrrhotite, pentlandite, and chalcopyrite-cubanite intergrowths--but makes up less than one wt. % of the massive ore samples. Although the maucherite grains appear homogeneous in reflected light, electron microprobe analyses show a wide range of variation in Ni/As and Fe/Ni ratios (Table 2, 3-5). One analysis of a Ni-As grain is clearly outside the range of maucherite compositions (2) and approaches the composition of niccolite (Table 2, 6). One micrometer-sized grain in maucherite gave an EDX spectra for osmium.

Platinum mineralization and maucherite have been reported in Keweenaw rocks (2 & 3), but the data reported here is the first identification we are aware of in the Duluth Complex. The new data emphasizes the need for evaluation of the ore recovery procedures which up to now have ignored special problems related to arsenide minerals. The data leaves the question of what phases are responsible for platinum metal group elements other than Pt in assay values unresolved (4).

Table 1. Samples of the Duluth Complex examined for arsenide minerals.

<u>Sample</u>	<u>Type</u>	<u>Location</u>
AMX-A	1 kg sample of massive sulfide, rich in chalcopyrite-cubanite	Supplied by MINNAMAX from an unspecified locality.
AMX-B	kg sized sample of massive sulfide, rich in pentlandite	Supplied by MINNAMAX from drift round #417, 1055 feet below reference in MINNAMAX shaft.
AMX-C	25 kg random massive sulfide ore sample.	From the MINNAMAX shaft dump.

Table 2. Electron microprobe analyses of arsenide minerals in the Duluth Complex.

Analysis	1	2	3	4	5	6
Sample	AMX-A3	AMX-A9	AMX-A1	AMX-A2	AMX-B4	AMX-B1
S	.10	.09	.04	.52	.11	.15
As	40.82	40.30	47.09	46.93	48.08	55.19
Fe	.77	1.01	.62	1.15	2.27	4.69
Co	.07	.10	2.38	3.18	1.97	.80
Ni	.76	.20	50.06	48.59	48.90	40.57
Cu	.13	.53	0	0	0	0
Zn	0	0	0	0	0	0
Pt	57.82	58.96	.06	.13	.09	.11
Total	100.47	101.19	100.25	100.50	101.42	101.51
S	.010	.008	.004	.054	.011	.018
As	1.670	1.612	2.085	2.081	2.122	2.800
Fe	.042	.054	.037	.068	.134	.319
Co	.004	.005	.134	.179	.111	.052
Ni	.040	.010	2.828	2.750	2.754	2.627
Cu	.006	.025	0	0	0	0
Zn	0	0	0	0	0	0
Pt	.908	.906	.001	.002	.002	.002
Anions	1.679	1.620	2.089	2.135	2.133	2.818
Cations	1.000	1.000	3.000	3.000	3.000	3.000
Total	2.679	2.620	5.089	5.135	5.133	5.818

Notes to Table 2:

Analyses were made on the ARL nine spectrometer electron microprobe in the Dept. of Geology, University of Wisconsin, Madison. Operating conditions: 15 K.V., 0.05 microamperes sample current; three replicate analyses with counting time sufficient to give accuracies of ± 5 wt. % of amount present for major elements and ± 50 wt. % for elements present at less than one wt. %. X-ray intensity data were reduced from mineral standards with standard ZAF corrections.

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Late and Post-Glacial Lacustrine Sediment Distribution in
Western Lake Superior from Seismic Reflection Profiles

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During the summers of 1982 and 1983, University of Minnesota researchers acquired over 700 km of high-resolution seismic profiles in the extreme western end of Lake Superior between Duluth and the Apostle Islands. The normal-incidence, 3.5 kHz single-channel seismic system employed had limited penetration of Proterozoic bedrock and Superior Lobe tills, but produced a clear and detailed acoustic picture of the fine-grained late and post-glacial lacustrine sediments.

The Duluth sub-basin has a subdued bathymetry compared with eastern Lake Superior's valleys and ridges. The basin between Duluth and the Apostle Islands deepens gradually from the west and south, but quite rapidly from the north, such that a deep trough runs parallel to the axis of the basin along the Minnesota shoreline. This depression is first distinguishable in the west near the mouth of the French River, and deepens and broadens northeastward, until it achieves a maximum depth of 290 meters off Silver Bay Minnesota.

The major stratigraphic components of the basin are Keweenaw clastic and volcanic rocks, unconsolidated Superior Lobe glacial tills of Wisconsinan age, and the post and late-glacial lacustrine sediments of Superior and earlier lakes. Till reflectors are commonly broad, diffuse and noisy, and are rarely traceable over more than a few kilometers. They appear only sporadically across the basin. The contact between the till and lacustrine sediments is generally parallel to the present-day lake bottom but in places may show relief several meters greater than the modern depositional surface. This contact is one of the most distinctive features on almost all the records and is defined by a crisp even-to-wavy or diffracted reflector which separates the noisy, commonly reflection-free till signature from the highly transparent lacustrine unit.

The lacustrine section typically contains numerous high continuity even-to-wavy reflectors which mimic the till-lake sediment contact. Maximum accumulations of fine-grained sediments, on the order of 25 meters, occur in the axis of the North Shore Trough. Reflectors within this unit are commonly parallel but within the trough onlap the steep trough sides and occasionally diverge down basin. Contorted reflectors and the lack of lacustrine sediments in certain areas suggest slumping has taken place on the flanks of the trough. Section thickness and reflector concentration increase from the basin edges to the basin deeps. Lacustrine sediment isopachs are grossly parallel to the bathymetric contours except in the extreme western portion of the area where an anomalous sediment distribution occurs. Off the French and Lester Rivers are concentrations of sediment of up to 20 meters which are not related to the modern bathymetry or modern sediment focusing effects. Between the two "mud patches," is an area of elevated acoustic basement, approximately 50 meters below the present lake level and buried

3-5 meters beneath fine-grained sediments, which externally resembles a broad, curved, spit-shaped sand body. A linear submerged ridge close and parallel to the Wisconsin shoreline also at depth of 50 meters appears to be an ancient low lake level strand line. These shallow water features suggest the past existence of a low lake stage 50 meters below current lake level.

Metamorphism of Kuruman and Griquatown Iron Formations and
Associated Makganyene Diamictite, Cape Province, South
Africa: A Stable Isotope Investigation

E. SCHUESSLER AND E.C. PERRY, JR. (Northern Illinois University)

Oxygen isotope geothermometry of cores of 2200×10^6 m.y. old Kuruman and Griquatown Iron Formations and overlying Makganyene Diamictite, Postmasburg Group, from cores near Postmasburg, Cape Province, South Africa indicate a maximum temperature of diagenesis/burial metamorphism of about 250°C . Large variations in the $\delta^{18}\text{O}$ of carbonates on the scale of cm indicates that the iron formation acted as a series of closed subsystems during diagenesis/metamorphism and has remained closed to post-metamorphic isotope exchange for 2×10^9 years. Thus, apart from metamorphic effects, these Proterozoic South African iron formations retain a record of primary isotope composition.

Proterozoic chemical sediments, including iron formations, are depleted in ^{18}O compared to modern cherts and carbonates. A possible explanation of this effect is high ocean temperature and consequent low chert-water isotope fractionation. The intimate association of Makganyene Diamictite of glacial origin and iron formation (Powell, this volume) effectively rules out such an explanation and implies that this iron formation was precipitated from water depleted in ^{18}O by about 10 ‰ compared to the modern ocean.

Carbon isotope composition of carbonate in core from the Makganyene Diamictite varies sympathetically with magnetite content in a way that suggests the reaction:

$5\text{Fe}_2\text{O}_3 + \text{C}_{(\text{organic})} \rightarrow \text{FeCO}_3 + 3\text{Fe}_3\text{O}_4$.
This relationship between carbonate and oxide iron minerals in the diamictite matrix reinforces the interpretation that these minerals were produced from active, chemically deposited iron-rich precursor phases and, thus, that diamictite deposition was, in part, contemporaneous with the chemical precipitation of iron formation minerals.

Oxygen isotopic study of two iron formation cores helps interpret diagenetic/metamorphic processes occurring in these rocks. In core CS119, carbonate is coarse-grained. Its $\delta^{18}\text{O}$ varies by only 1 ‰ suggesting low-temperature exchange with magnetite and SiO_2 , followed by carbonate recrystallization and isolation from further isotopic exchange. In CS120, $\delta^{18}\text{O}$ of carbonate varies by several ‰ and is correlated on a cm scale with per cent magnetite. A consequence of this pattern is that several apparent siderite-magnetite oxygen isotope temperatures from this core are about 100°C higher than quartz-magnetite temperatures, while quartz-siderite "temperatures" are often below 0°C . To explain oxygen isotopic values for quartz, magnetite, and siderite in this core, it is necessary to postulate that siderite exchanged ^{18}O with magnetite at relatively low temperature, then ceased to react while magnetite continued

to exchange isotopes with quartz to temperatures of about 250°C. Thus, it appears that before crystallization siderite is more reactive than quartz whereas after recrystallization it is relatively isolated from further oxygen isotope exchange. Other explanations are inconsistent with isotope geothermometry.

Early Proterozoic Penokean Igneous Rocks of the Lake
Superior Region: Geochemistry and Tectonic Implications

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The nature and composition of igneous rocks from ancient terranes can provide significant insights into the tectonic processes active during their formation. Until recently only limited data were available for the Early Proterozoic Penokean (1900-1840Ma) igneous rocks of the Lake Superior region, particularly those that constitute the volcanic-plutonic terrane of northern Wisconsin. However, with the recent review of available major element data for volcanic rocks of the region by Greenberg and Brown (1983), the acquisition of trace-element data (including rare-earth element data) for the volcanic rocks of upper Michigan (Fox, 1983) and northern Wisconsin (Schulz, 1983), and the documentation of the compositional characteristics of the granitoid rocks in northern Wisconsin (Schulz and others, 1983), the nature and compositional affinities of the igneous rocks can now be more fully evaluated and used to understand the tectonic activity during the Early Proterozoic Penokean evolution of the region.

In upper Michigan, Penokean igneous rocks within the dominantly sedimentary Marquette Range Supergroup consist of basalt flows and gabbroic sills, and lesser amounts of basaltic and rhyolitic volcanoclastic rocks. These suites are distinctly bimodal with basalt and lesser rhyolite predominant, show strong tholeiitic iron enrichment trends, and relatively high concentrations of large-ion lithophile (LIL) elements. The rocks are compositionally similar to continental-rift and plateau volcanics such as those of the Keweenaw Supergroup of the Lake Superior region and those of the Columbia River Basalt Group of Washington, Oregon, and Idaho.

In northern Wisconsin, Penokean volcanic sequences within the volcanic-plutonic terrane consist of basalt through andesite and rhyolite flows and pyroclastics with associated subvolcanic intrusives. These volcanic rocks are dominantly calc-alkaline and are enriched in LIL elements (i.e., $[La/Yb]_N = 2.5-9.4$) but are depleted in high-field-strength elements (i.e., Hf, Zr, Ta, etc.) and are similar to volcanic sequences found in recent island-arcs (e.g., New Hebrides and Japanese arcs). In contrast, the basalts of the Quinnesec Formation from northeastern Wisconsin are tholeiitic in character, are strongly depleted in LIL elements [i.e., $[La/Yb]_N = 0.09-0.89$], and are compositionally similar to recent back-arc basin basalts (e.g., Lau Basin) and island-arc tholeiites (e.g., Scotia arc).

The Penokean granitoid rocks of northern Wisconsin show a temporal progression from gabbro and diorite through tonalite to granite. These rocks are mostly calc-alkaline, although slightly alkaline varieties (i.e. Marinette Quartz Diorite, northeastern Wisconsin) are also present. The granitoids show an increase from north to south across the terrane in their K_2O/Na_2O ratios and overall SiO_2 contents. They are compositionally similar to granitoids found in modern, evolved island-arcs (e.g., Japan) and continental convergent-plate-margin settings (e.g., Sierra Nevada batholith).

The nature and geochemistry of the Early Proterozoic Penokean igneous rocks of the Lake Superior region strongly suggest the operation of plate-tectonic processes largely similar to those active today. The data support a tectonic model of 1) early crustal rifting (bimodal basalt-rhyolite volcanism, upper Michigan) and spreading, 2) subsequent subduction and formation of a complex volcanic arc (tholeiitic, and calc-alkaline volcanism and plutonism, northern Wisconsin), and collision of the arc first with Archean crust on the south and then with the continental-margin sequence and Archean crust of upper Michigan on the north (i.e., the Penokean Orogeny).

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Regional Controls of Lower Precambrian Metallogeny
in the Upper Peninsula of Michigan

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This is an attempt at finding any large scale regional controls of metallogeny in the Upper Peninsula of Michigan. To limit the extent of this study we are restricting the scope of it to Archean and lower middle Precambrian sections and not including the Keweenaw which has obvious structural controls at a regional level. We have gathered an information base of structural and lithologic trends from both large scale (1:250000) and small scale (1:24000) maps and an unpublished M.S. thesis by Bodwell (1972, MTU). Bodwell covered all reported metal locations and this was used as the primary data-base.

By plotting structure and lithology on a base map and making overlays of different metal associations (Au + Cu + Ag, Au + Ag, Au + base metal sulfides, Cu + Mo, base metal sulfides) regional structural/lithologic metallogenic patterns are shown, if present. For purposes of simplification the Upper Peninsula has been divided into three areas: The Marquette Range, The Gogebic-Watersmeet area, and the Crystal Falls-Menomonee-Iron River areas. This is based on some physical separation of these areas. These areas have a common Paragenesis although stratigraphic columns are not exactly the same.

After following this procedure hopefully some relations will become apparent. At this point my research is not complete but some apparent trends are present. In the Gogebic-Watersmeet area gold deposits seem to be confined to a greenstone belt and the very near proximity. In the northern Marquette Range base metal deposits follow the limbs of an apparent fold.

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Trace Element Geochemistry of Some Lake Superior
Keweenawan Basic Layered Intrusions

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Seven REE (La, Ce, Sm, Eu, Tb, Yb, and Lu), Co, Cr, Th, Hf, Ta, Sr, Rb, and Ba have been determined by instrumental neutron activation analysis (INAA) for rocks from the Duluth complex, Mineral Lake intrusion, and the Rearing Pond intrusion. The trace element characteristics of the various units comprising these intrusions can be combined in their appropriate abundances to derive the character of their parental magmas. For the Mineral Lake intrusion, this calculated composition is compared to a chill zone sample and found to be markedly different. Insufficient data are available on the Rearing Pond intrusion to calculate a parental magma composition.

The parental magma compositions are compared to the most primitive North Shore volcanic composition to test for a genetic relationship. It is not possible to derive the intrusive parental magmas from the most primitive North Shore volcanic composition by magmatic differentiation alone. The various parental magmas can only be related by more complex models.

Dikes as Tectonic Indicators in the Eastern Lake Superior Region - Structural and Paleomagnetic Considerations

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The majority of Archean rocks have undergone complex Early Precambrian deformation, and thus, are of limited use in defining the nature and timing of post-Archean tectonic events. It is clear, however, from the abundance of faults and shear-zones in shield areas that later Precambrian tectonic events of some kind have indeed occurred. Where a shield is overlain by Middle to Late Precambrian volcanic/sedimentary sequences, tilting, fault displacement, and other deformational features can often be directly observed and constraints placed on the age and extent of deformation. For the most part, however, such Precambrian cover rocks are confined to localized areas on shield margins.

Ernst and Halls (1984) have shown from a study of dikes in the Kapuskasing Zone, that dike attitudes and paleomagnetic signatures may be used as tectonic indicators in the Canadian Shield. In their study, dikes of the same swarm which differed from the norm both in attitude and paleomagnetic direction were used to show a westward tilting of the crust in association with upthrusting along the eastern margin of the Zone.

Patches of lakeward-dipping Keweenawan volcanics and sediments show that the shield along the coast of Lake Superior has been involved in basin subsidence. These Keweenawan rocks, however, are only rarely found along the eastern shore and thus are insufficient to define the full extent of shield deformation associated with basin development. On the other hand, dikes are pervasive both on the Lake Superior coast and in the interior of the shield. Nuffield (1951) observed that the dikes in the Montreal River Harbour area dip NE; dikes north and east of the lake have been observed to be near-vertical. This is an ideal environment in which to apply and extend the findings of Ernst and Halls.

In addition, the Montreal River follows a major fault that may be the southern extension of the eastern boundary thrust of the Kapuskasing Zone. It was thought that if faulting had been of major extent, an overprint dating from fault movement (and Kapuskasing activity in general) would be evident in the paleomagnetic signature of dikes cutting the fault.

The purpose of this study, then, was to use the paleomagnetic signature and attitude of dikes to 1) determine the nature and extent of eastern-shore shield deformation related to Keweenawan basin subsidence and 2) look for signs of Kapuskasing activity along the Montreal River fault.

Thirty-nine paleomagnetic sites comprising a total of 300 samples were collected from northwest-trending diabase dikes along two traverses roughly normal to the eastern shoreline of Lake Superior and oblique to the trend of the dikes. The northern traverse, about 45 km long, follows the Montreal River to the coast. Since it was important to know the structure and paleomagnetism of dikes in a relatively stable area, a southern traverse—remote from possible influences of Kapuskasing and Lake Superior deformation—was chosen as a control. This traverse is located 5 to 10 km south of the northern traverse, 35 km from the coast, and extends eastward for a distance of 70 km. Twenty-three dikes in the southern traverse and sixteen dikes in the northern traverse were sampled.

Based on paleomagnetic direction, there appear to be at least four ages of dike intrusions in the interior corresponding to Keweenaw, Sudbury, Matachewan and an undated dike set which cuts a Huronian outlier and has a similar paleomagnetic direction to that of Abitibi and Preissac dikes. All sampled interior dikes trend NW to N, and beyond about two km from the shoreline, dip less than 5 to 10 degrees from the vertical. In the field, samples generally appear fresh, though apparent deuteric alteration is present in some margins. Dikes within about two km of the shoreline tend to have a more westerly trend and all dip NE at angles ranging from 45 to 70 degrees. These dikes, in comparison with those of the interior, are more altered and sheared, especially at the margins.

An easterly rotation of approximately 40 degrees about a NW axis returns both the attitude and paleomagnetic direction of the coastal dikes to those of the control group. This is in agreement with the rotation needed to return the Keweenaw rocks in the south to the horizontal. The combination of rotated attitudes and paleomagnetic poles—and also the large degree of shearing—indicates that the present anomalous dips and strikes of the coastal dikes are due to tectonic rotation and not to a geographic change in orientation of the tensional environment during emplacement. In addition, the study shows that, at least locally, a rim of shield no more than 2 km wide has been tilted in response to subsidence in the Lake Superior Basin.

Preliminary structural and paleomagnetic data from the NW trending dikes cutting the Montreal River Fault suggest that little activity has occurred in the area since emplacement of these dikes.

Characterization of the Ore Host Rock at the
Ropes Gold Mine, Ishpeming, Michigan

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Gold mineralization at the Ropes Gold Mine is contained within an east-west trending, nearly vertical, tabular, schistose rock body which is surrounded by the Deer Lake Peridotite. The ore host rock (OHR) can be divided into four mappable units based on the relative abundance of layer silicate minerals, which make up the majority of the OHR, and whole rock chemical composition: 1) mostly sericite; 2) about equal amounts of sericite and chlorite; 3) mostly chlorite; and 4) chlorite and carbonate. Quartz is ubiquitous throughout all the units. Disseminated pyrite and lesser amounts of magnetite are also present. The carbonate is dolomite with minor ankerite. Disseminated gold is most abundant in the more sericitized and silicified units. However, the highest gold values in the mine are associated with quartz-sulfide veins which were the target for the early mining. These veins are cross-cut by barren carbonate veins.

The layer silicate minerals within the various OHR units can be distinguished by composition, structural type and textural criteria. In general, chlorites are clinocllore but in detail can be subdivided into: Type 1) an early fine-grained, lower ordered Ib chlorite, relatively enriched in Mg and Si with a composition of $[(Mg_{11.2}Fe_{0.8}^{+2})(Si_{7.1}Al_{0.9})O_{20}(OH)_{16}]$ which commonly defines foliations and is a major component of the matrix; and Type 2) a later porphyroblastic, higher ordered IIb chlorite, which is relatively higher in Fe and Al with a composition of $[(Mg_{8.7}Fe_{3.3}^{+2})(Si_{5.8}Al_{2.2})O_{20}(OH)_{16}]$. Sericites are essentially an ideal K, Al muscovite with low Na, Fe and Mg and can also be subdivided into two varieties: Type A) an early fine-grained $2m_1$ mica which commonly occurs in discrete blebs or in torn fragments; and Type B) a later highly crystalline, coarser $2m_1$ mica which commonly occurs in the matrix. The Type 1 chlorites are restricted to the less intensely altered gold-poor chlorite and chlorite-carbonate units of the OHR whereas Type 2 chlorites and Type B sericites are predominantly found in the more gold-rich sericite and sericite-chlorite units. The chlorite polytypes suggest that the later Type 2 chlorite was formed at a higher temperature than the earlier Type 1 chlorite and may be a recrystallization product of Type 1. Their compositions reflect the composition of the fluid, rock and water/rock ratios. The overall distribution of the various types of layer silicate minerals within the OHR may be a reflection of hydrothermal gradients established during mineralization.

The OHR is interpreted as an altered and sheared rock and, as such, there is only speculative evidence as to the original protolith. Whole-rock major and trace element data on 63 samples indicate that the sericite, sericite-chlorite and the chlorite units are compositionally different than the Deer Lake Peridotite. However, the chlorite-carbonate unit is similar in some respects to the peridotite. Immobile element ratios suggest that the sericite unit is similar to andesitic members of the Kitchi Schist.

Petrographic and Geochemical Study of the Mount Bohemia Stock,
Portage Lake Volcanics, Keweenaw Peninsula, Michigan

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Mount Bohemia is a small stock (284 x 146 m) intruded into the lower section of the Portage Lake Volcanics. The majority of Mount Bohemia stock is an altered, medium- to coarse-grained diorite. It has a reconstructed primary mineral assemblage of 45% to 50% sodic plagioclase, 30% to 50% mafic minerals (augite and hornblende), and up to 3% quartz. In addition, considerable amounts of magnetite (exceeding 15% in some areas) are more or less ubiquitous throughout the rock body. A small section in the southeastern portion of the body is composed of fine-grained quartz diorite with a reconstructed primary mineral assemblage of approximately 60% sodic plagioclase, 30% quartz, and 7% biotite. A much smaller concentration of magnetite, about 3%, is found in this section of the intrusive. Presumably this quartz diorite is representative of the final stages of intrusive activity.

The diorite has been moderately to severely altered. The alteration shows a strong correlation with the Lac La Belle fissure, a structural feature striking N20°W through the intrusive, indicating a preferential channeling of hydrothermal fluids. Potassium metasomatism is pervasive, although heaviest along the fissure, and secondary potassium feldspar is microscopically observable in almost all thin sections. This, combined with the alteration of primary magnetite to fine-grained hematite, is responsible for the pinkish coloration that gives hand specimens the misleading appearance of a syenite. Alteration products which are related to the fissure position are: serpentine (from mafics); epidote (from plagioclase, mafics); and calcite (from plagioclase). Alteration products whose abundance is inversely related to the position of the fissure include: actinolite (from pyroxene) and sericite (from plagioclase). Alteration of mafic minerals to chlorite occurs everywhere and it is the alteration product of the biotite in the fine-grained quartz diorite.

Geochemical variations within the intrusive follow a few general trends. Concentrations of mobile elements such as Cu, Zn and Rb are higher along the Lac La Belle fissure. High Rb concentrations can be specifically correlated with the presence of secondary K-feldspar. Immobile elements such as Zr, V and Ni have relatively uniform values throughout the diorite rock body. Cr varies in a manner which might be related to original magmatic processes. The concentrations of immobile elements are distinctly different between the main diorite rock body and the later-stage quartz diorite. The Zr concentration is higher in the more silicic rock, and Cr and V concentrations are lower.

A partisan review of the Early Proterozoic geology
of Wisconsin and adjacent Michigan

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Two contrasting sequences of Early Proterozoic rocks are present in the Wisconsin-Michigan region: a northern epicratonic sequence of interbedded sedimentary and volcanic rocks (Marquette Range Supergroup of Michigan) overlying Archean basement, and a southern terrane dominantly composed of volcanic and granitoid rocks and generally lacking Archean basement (Wisconsin magmatic zone). The boundary between the two terranes, at least in northeastern Wisconsin, is the Niagara fault.

The Marquette Range Supergroup is composed of three depositional cycles separated by minor unconformities. In general, the deposits fine upward: basal clastic and chemical deposits, accumulated in rift basins and on platforms (Larue and Sloss, 1980), are succeeded upward by quartzose sandstone and the major iron-formations of the region. These strata are overlain by a southward-thickening wedge of turbidites, areally restricted iron-formations and, in more southerly parts, intercalated submarine volcanic rocks, which are mainly pillow basalts. The depositional patterns indicate a shelf prograding into a deep water environment, the detritus being derived principally from exposed Archean rocks to the north. Deposition took place on a passive continental margin. Sedimentation ceased before or during the main pulse of deformation accompanying the Penokean orogeny. Deformation involved sub-horizontal compression accompanied by substantial shortening of the supracrustal sequence (Cannon, 1973) and, later, dominantly vertical tectonism associated with the development of diapiric gneiss domes caused by reactivation of Archean basement gneiss. An annular pattern of metamorphism around some of the gneiss domes was superposed on regional greenschist metamorphism.

The age of the Marquette Range is poorly defined, but it is bracketed between 2,120 m.y. (mafic dikes in basement; Beck and Murthy, 1982) and 1,820 m.y., the age of a granite body at Lake Mary, Mich., that cuts the supergroup. The volcanic rocks in the supergroup as indicated by rhyolite in the Hemlock Formation, are about 1,900 m.y. old (W. R. Van Schmus, written comm., 1983). They are largely bimodal with abundant tholeiitic basalt and minor high K_2O rhyolite. The basalt shows strong iron enrichment, and high TiO_2 and incompatible-element contents (Fox, 1983); it is compositionally similar to continental basalts.

Except in a broad sense, a coherent, integrated view of the Wisconsin magmatic zone is lacking, partly because of meagre exposures and partly because of the inherent difficulties of deciphering thick, complexly disturbed volcanic accumulations. As a generalization, the magmatic zone is composed of calc-alkaline volcanic and intrusive rocks having overall island-arc affinities, and more restricted granitoid gneisses.

A key area for understanding the stratigraphy, metamorphism, and tectonic evolution of the magmatic terrane is the Dunbar dome and vicinity in northeastern Wisconsin. The dome is a large-scale, antiformal fold-

interference structure about 20 km in diameter, modified by diapirism and by intrusion of tonalite, granodiorite, and granite. It provides a window exposing older gneiss that evolved at a deeper crustal level than the widespread supracrustal rocks. The gneiss and the immediately adjacent supracrustal rocks are amphibolite facies, whereas the regional metamorphic grade of the supracrustals in the area is greenschist facies. The stratigraphic succession in the dome area, from oldest to youngest, is (1) gneiss, migmatite, and amphibolite (Dunbar Gneiss of Cain, 1964), (2) shallow-water sedimentary rocks, (3) basalt-andesite-dacite (Quinneseec Formation), and (4) rhyolite. The rhyolite appears to be younger than the major deformation and metamorphism. In a broad sense, this stratigraphic succession appears to fit the other gneiss-granitoid domes across northern Wisconsin.

A similarly complex stratigraphy of Early Proterozoic rocks has been determined in central Wisconsin (LaBerge and Myers, 1984). At least three successions of volcanic rocks are distinguished on the basis of differences in composition, metamorphism, and structural fabric. An older, widespread subaqueous basaltic succession with abundant mafic subvolcanic intrusion breccias, mainly of amphibolite facies, is overlain locally by subaqueous felsic-intermediate volcanic rocks and intercalated sedimentary rocks of upper greenschist facies. At Wausau, a still younger, weakly metamorphosed, partly subaerial volcanic-sedimentary succession is present. Distinct episodes of granite emplacement followed extrusion of the older basalt and the younger volcanics at Wausau; the younger granites are leucocratic and have high K_2O/Na_2O ratios. The age of the volcanic successions relative to the Early Proterozoic gneisses and foliated tonalite associated with Archean gneiss in central Wisconsin (Maass, 1983) is equivocal, but we interpret the volcanic successions as being younger; the gneisses are representative of a deeper crustal level than the volcanic rocks.

All the volcanic rocks in Wisconsin (regardless of stratigraphic age) and the associated granitoid rocks have U-Pb zircon ages of about 1,850 m.y. (Van Schmus, 1980). Detailed zircon dating in northeastern Wisconsin (Peterman, unpublished data) indicates that the volcanic and granitoid rocks crystallized in the short time span of 30 m.y., from 1,865 to 1,835 m.y. ago.

The structure of the Early Proterozoic rocks in Wisconsin is complex. On a regional scale, the terrane consists of generally large structural blocks having diversely oriented internal structures that are bounded by ductile deformation zones ("shear zones"). The deformation zones record pronounced flattening in the foliation planes and a strong component of vertical movement (Palmer, 1980). Although deformation is intense in the shear zones, it is regional in scope, and generally is younger than the prevailing internal structural fabric within the blocks.

The boundary between the northern and southern Early Proterozoic terranes, as indicated by the Niagara fault, is marked by structures indicative of variable but generally high strain (Larue, 1983). On both sides of the fault, the rocks generally have a steep south-dipping foliation that is subparallel to the fault and a generally steep southwest-plunging stretching lineation. These data, together with high-angle reverse faults on the north side of the shear zone (Bayley and others, 1966), suggest that the Niagara fault itself is steeply inclined southward. The westward continuation of the

fault is conjectural, although a fault is shown on the regional geologic map (Morey and others, 1982).

Differences in lithology, chemical composition of volcanics, and metamorphic and structural style suggest that the two Early Proterozoic terranes largely evolved separately. Several plate tectonic models involving some combination of rifting, subduction, and collision have been proposed to explain the evolution of the Early Proterozoic rocks in the Michigan-Wisconsin segment of the Lake Superior region as well as the nature of the Penokean orogeny (Van Schmus, 1976; Cambray, 1978; Larue and Sloss, 1980; and Greenberg and Brown, 1983). On the basis of new chemical and structural data, Schulz and others (1984) have proposed a tectonic model of early crustal rifting and spreading, subsequent subduction and formation of a complex volcanic arc, and collision of the arc, first with Archean crust on the south and then with the continental margin (epicratonic) sequence and Archean crust of upper Michigan on the north (the Penokean orogeny). Culmination of the orogeny was approximately 1,850 m.y. ago.

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Morphology, Accretion Rate and Microstructure
of Recent Algal Stromatolites from
Eagle Lake, Ottertail Co., MN

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Hardened, high relief organo-sedimentary carbonate structures (stromatolites) have been discovered growing as cauliflower-like mounds on cobbles and boulders in water depths of between 11 and 15m along the south shore of Eagle Lake, Ottertail Co., MN. The lake is an exceptionally clear, hard-water, kettle moraine lake. The stromatolites begin as encrustations (on cobbles and boulders), which gradually evolve into hemispheroidal columns 0.5 to 0.8m in height. The stromatolite surface is covered by a green mat of filamentous algae - Cladophora aegagropila rabenhorst. A botryoidal surface growth form merges into an interior with numerous interconnecting cavities which are populated by gastropods, leeches, and other organisms. X-ray diffraction analysis indicates that most of the lithified interior consists of low-magnesium calcite. The dominant interior microstructure, as revealed by thin-sections and scanning electron microscopy, consists of non-laminated, anhedral calcite crystals and diatoms. This microstructure suggests that settling lake carbonates have been trapped and bound by the filamentous algae. Subsequent cementation occurs by photosynthesis induced precipitation of calcite from the saturated lake water. Observable in scanning electron micrographs as well as in thin-sections are areas which show laminations. These laminated areas make up less than 5% of the stromatolite and appear to form in recesses where the bioinduced precipitation is not being diluted by the more rapidly settling lake carbonates. This bioinduced precipitate consists of a mosaic of smaller uniformly sized anhedral calcite crystals measuring 1-5 μ . Preliminary uranium-thorium series dating suggests that the rate of accretion is extremely slow. A sample obtained from inside a 0.5m thick stromatolite indicated an age in excess of 10,000 years.

This observed stromatolite formation in a relatively deep fresh-water environment may necessitate a re-evaluation of their generally accepted paleoenvironmental interpretation.

Geologic History and Palinspastic Reconstruction of the
Early Proterozoic Penokean Collision Zone

By

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There are two principal early Proterozoic tectonic elements in the southern Lake Superior region: a northern passive margin assemblage, and a southern magmatic arc assemblage, juxtaposed along the Florence-Niagara fault. The passive margin assemblage, representing the southern terminus of the Superior province of the Canadian Shield, is locally fragmented into two discrete blocks next to the contact with the magmatic assemblage; the Florence-Niagara and Crystal Falls terranes. These terranes are stratigraphically comparable but disjunct from the rest of the passive margin.

Paired shear zones straddle the Florence-Niagara fault: to the north of the fault, highly-deformed strata of the Florence-Niagara terrane define the northern shear zone; to the south of the fault, highly-deformed rocks of the northern margin of the magmatic terrane define the southern shear zone. There has been little or no material transfer across the fault. These paired shear zones were probably formed during terrane accretion.

The entire region has been deformed by probably five deformation events. This has been precisely documented only north of the Florence-Niagara fault, but preliminary data to the south support this contention. The parallel deformation histories shared by different terranes in this region indicate that a NNE oriented shortening regime of the first deformation was responsible for the terrane accretion. Throughout the region, the F1 deformation left a set of penetrative foliations oriented N70W 90 and a series of tight folds which sometimes involved Archaean crystalline basement, such as at the Amasa Oval. The second phase of deformation is characterized by planar elements oriented N65E 90; F1 elements are locally crossfolded by this deformation. The bending of originally N70W-trending F1 structures into a N15W orientation is concentrated in a 50 km wide NE-trending band cutting through approximately Crystal Falls, Michigan, up toward the southern tip of the Republic trough. To the southwest, this F2 deformation band bends the Florence-Niagara Fault. The location of this band was probably controlled in part by structures in the underlying basement. The Amasa Oval represents one such product of crossfolding and does not represent a gneiss dome.

We propose that the southcentral Lake Superior region was originally characterized by W-NW trending structures resulting from terrane accretion. This regional structure was modified by the NE-trending deformation band which rotated previous W-NW trending structures.

Recent Contributions to the Geochronology of the
Precambrian of Wisconsin

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Continued U-Pb age studies on zircons from Precambrian units throughout central and N Wisconsin have helped to document in more detail the occurrence of rocks formed during the main phase of the Penokean Orogeny in Wisconsin and have improved our understanding of the Archean block of central Wisconsin. In addition, results from several localities seem to confirm the presence of pre-Penokean Early Proterozoic igneous units in Wisconsin.

Based on previous and new results, it still seems best to bracket the main phase of Penokean Orogeny between 1830 and 1860 Ma. The tendency for plutonic units with ages in the older part of this range to be more strongly foliated is still pronounced, but not universal. Several units have also been found that yield apparent ages from 1870 to 1920. In some cases it is possible these are Penokean units with an inherited older component in the zircons, but if so this is not obvious. Furthermore, in some cases with ages of 1890 to 1915 Ma this possibility has virtually been ruled out. Thus, these ages around 1900 Ma probably represent true ages, and the rocks from which they were obtained are tentatively interpreted as remnants of one or more older, pre-Penokean (or earlier Penokean) igneous suites. Most of these units are tonalitic, deformed, and scattered over a large area, so that no single, coherent older Proterozoic terrane or domain can be identified at present.

Tonalitic gneiss near Marshfield, along the northern edge of the Central Wisconsin Archean block, yields zircons with complex U-Pb discordance patterns. However, it is clear that these zircons are about 3000 Ma old, consistent with earlier results suggesting that this Archean terrane may be a remnant of the older gneiss-migmatite province of the southern Lake Superior region. Zircons separated from felsic gneiss near Fifiield also indicate an age of 2950 to 3000 Ma, suggesting that the Archean block in central Wisconsin is related to the older gneisses in northwestern Wisconsin.

The overall tectonic picture preferred by the author is still one in which most of the Penokean igneous suite of northern Wisconsin was formed in continental margin arc complexes, and that more than one distinct period of subduction-generated magmatism occurred within the interval 1920 to 1820 Ma. However, outcrop and geochronologic control is still insufficient to constrain the model precisely.

The Huronian Supergroup: An Example of an Early Proterozoic
Passive Margin Sequence

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Information on passive margin successions such as those of the peri-Atlantic region has come from geophysical work and drilling. The stratigraphic succession differs in different areas but the classical model involves alkaline volcanics and continental sediments deposited in fault-bounded troughs, followed by evaporites and, above the "break-up" unconformity, a continental margin succession comprising the terrace wedge and continental rise successions.

Huronian stratigraphy has largely been interpreted in terms of a tripartite cycle involving diamictites, argillites and sandstones in ascending sequence. It is here suggested that the Huronian succession (10-12 km in max. thickness) may be the result of continental fragmentation. The lower Huronian, below the Cobalt Group, includes syn-rift volcanics chemically akin to those of the Afar Triangle and largely continental clastic sediments such as those of the Mississagi and Serpent Formations. These formations are of limited distribution and display major thickness and facies changes consistent with contemporaneous fault activity. Evaporitic facies may be represented by carbonates of the Espanola Formation near the top of the lower Huronian succession.

The boundary between the lower and upper Huronian is taken as the base of the Gowganda Formation. In the southern part of the Huronian outcrop belt there is a profound change from a basin-full condition to one in which resedimented glaciogenic rocks predominate. The boundary is interpreted to mean a sudden tectonic foundering of the basin. In more northerly areas there is an angular unconformity between the Gowganda and underlying lower Huronian formations and still farther north the Gowganda Formation lies directly on Archean basement rocks. These relationships indicate both local and regional subsidence and the transition from a dominantly continental to marine shelf-type sedimentation. Relationships at the base of the Gowganda Formation are equated to the "break-up" unconformity that characterizes many younger continental margin assemblages. It differs, however, in bearing evidence of contemporaneous glaciation. Similar resedimented glaciogenic facies are associated with late Proterozoic continental fragmentation in the Cordilleran region.

Rocks of the lower Huronian do not appear to be represented in the Lake Superior region, probably because the early rifting did not extend that far west but the transgression associated with the regional subsidence phase led to deposition of glaciogenic and succeeding marine platformal facies of the Chocoy Group and possibly the Mille Lacs Group which are considered to be equivalent to the upper Huronian.

The tectonic setting of the Huronian and equivalent rocks remains obscure but thickness and facies changes and regional paleocurrent data suggest that they were formed in an intracratonic rift setting with subsequent ocean opening to the east to explain the regional subsidence in Gowganda times. The subsequent history of early Proterozoic rocks of the south shore of Lake Superior has been interpreted by several workers to involve a period of ocean opening and closure.

Reference

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