



INSTITUTE ON LAKE SUPERIOR GEOLOGY PROCEEDINGS

VOLUME 35

MAY 1989

Part 1. Abstracts



**35th Annual Meeting
May 3-6, 1989
held at
Duluth, Minnesota 55812**

Organizing Committee, 35th Annual Meeting, ILSG (1989)

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Volume 35 consists of Parts 1 and 2:

- 1: Abstracts**
- 2: Field Trip Guidebooks**

Published and Distributed by
Institute on Lake Superior Geology
J. Kalliokoski, Secretary/Treasurer
Dept. of Geological Engineering, Geology and Geophysics
Michigan Technological University
Houghton, Michigan 49931

ISSN 1042-9964

35th ANNUAL
INSTITUTE ON LAKE SUPERIOR GEOLOGY

Proceedings and Abstracts

Duluth, Minnesota

May 4 and 5, 1989

Organized by

Richard W. Ojakangas, University of Minnesota, Duluth
John C. Green, University of Minnesota, Duluth
Timothy B. Holst, University of Minnesota, Duluth

Program Chairman and Editor: John C. Green

Volume 35. Part 1 Program and Abstracts
Part 2 Field Trip Guidebooks

COVER Anticline in Thomson Formation at Thomson
dam near Thomson, Minnesota. View from
east bank of St. Louis River, looking
west. Wendell Wilson 5/30/1968

PURCHASE OF PROCEEDINGS AND ABSTRACTS AND FIELD GUIDEBOOKS

The Proceedings and Abstract and the Field Guidebooks for the 35th Annual Institute on Lake Superior Geology may be purchased by contacting:

John C. Green
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INSTITUTES ON LAKE SUPERIOR GEOLOGY

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

CONSTITUTION OF INSTITUTE ON LAKE SUPERIOR GEOLOGY

Article I Name

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

Article II Objectives

The objectives of this organization are:

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

Article III Status

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

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

Minn. Stat. Anno. 290.01, subd. 4
" " " 290.05(9)
1954 Internal Revenue Code s. 501(c)(3)

Article IV Membership

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

Article V Meetings

The organization shall meet once a year, preferably during the month of April. The place and exact date of each meeting will be designated by the board of directors.

Article VI Directors

The board of directors shall consist of the Chairman, Secretary-Treasurer, and the last three past Chairmen; but if the board should at any time consist of less than five persons, by reason of unwillingness or inability of any of the above persons to serve as directors, the vacancies on the board may be filled by the annual meeting so as to bring the membership of the board up to five members.

Article VII Officers

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

- A. The Chairman shall be elected each year by the board of directors, who shall give due consideration to the wishes of any group that may be promoting the next annual meeting. His term of office as Chairman will terminate at the close of the annual meeting over which he presides or when his successor shall have been appointed. He will then serve for a period of three years as a member of the board of directors.
- B. The Secretary-Treasurer shall be elected at the annual meeting. His term of office shall be two years or until his successor shall have been appointed.

Article VIII Amendments

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

BY-LAWS

I. Duties of the Officers and Directors

A. It shall be the duty of the Chairman to:

1. Preside at the annual meeting.
2. Appoint all committees needed for the organization of the annual meeting.
3. Assume complete responsibility for the organization and financing of the annual meeting over which he presides.

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

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

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

II. Dues and Expenses

1. There shall be no regular membership dues.
2. Registration fees for the annual meetings shall be determined by the Chairman in consultation with the board of directors. It is strongly recommended that these be kept at a minimum to encourage attendance of graduate students.

III. Rules of Order

The rules contained in Robert's Rules of Order shall govern this organization in all cases to which they are applicable.

IV. Amendments

These by-laws may be amended by a majority vote of those persons who are personally present at, participating in, and voting at any annual meeting of the organization; provided that such modifications shall not conflict with the constitution as presently adopted or subsequently amended.

Award Guidelines
SAM GOLDICH MEDAL

Preamble

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

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

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

Award Guidelines

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

April 4, 1981

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

STUDENT TRAVEL AWARD

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

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

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

BOARD OF DIRECTORS

1989

R.W. Ojakangas (with J.C. Green and T.B. Holst), Department of Geology,
University of Minnesota, Duluth, Duluth, Minnesota 55812

1988

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

1987

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

1986

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

Secretary-Treasurer

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

LOCAL COMMITTEE

R.W. Ojakangas: General Chairman

J.C. Green: Program Chairman; Program and Abstracts editor

T.B. Holst: Field Trip Chairman; Field trip arrangements and field trip
guidebook editor

BEST STUDENT PAPER COMMITTEE

J.S. Klasner: Western Illinois University, Macomb, Illinois

Ray Anderson: Iowa Geological Survey, Iowa City, Iowa

Keith Laskowski: Newmont Exploration, Ltd., Duluth, Minnesota

GOLDICH MEDAL COMMITTEE

J.J. Brummer: Brummer Consulting, Toronto, Ontario

M.G. Mudrey, Jr.: Wisconsin Geologic and Natural History Survey, Madison,
Wisconsin

R.W. Ojakangas: University of Minnesota-Duluth, Duluth, Minnesota

GOLDICH MEDAL RECIPIENT

Jorma Kalliokoski, Michigan Technological University (Professor Emeritus).
Medal awarded by M.G. Mudrey, Jr., Wisconsin Geological and Natural
History Survey

BANQUET SPEAKER

S.F. Sawkins, University of Minnesota, Twin Cities, "Ore genesis models for
volcano-plutonic arc systems: an agnostic view of the conventional wisdom"

ACKNOWLEDGMENTS

Several people and organizations assisted in preparation of the 35th Annual
ILSG. Without their help the many tasks in preparing this meeting could not
have been done. The three of us (R.W. Ojakangas, J.C. Green, and T.B. Holst)
would like to thank the following people and organizations for their help.

Mary Nash, Executive Secretary, Department of Geology, University of
Minnesota-Duluth, for handling finances and other aspects.

Joan Hendershot, Senior Secretary, Department of Geology, University of
Minnesota-Duluth, for various tasks.

Avis Hedin, Principal Secretary, College of Science and Engineering, University
of Minnesota-Duluth, for typing.

Linda Solcich, Radisson Hotel, Duluth, for meeting site arrangements.

John Klasner, Department of Geology, Western Illinois University, for mailing
lists and advice.

Graduate students at University of Minnesota-Duluth, for performing tasks,
including mailing brochures and projection.

Numerous company personnel for cooperation on field trips.

University of Minnesota-Duluth, for assistance with transportation.

Everyone else.

34TH ANNUAL INSTITUTE ON LAKE SUPERIOR GEOLOGY
Marquette, Michigan, 1988

The 34th annual meeting of the Institute on Lake Superior Geology was held from May 10-14, 1988, in Marquette, Michigan. The meeting was co-hosted by Northern Michigan University, the U.S. Geological Survey-Branch of Eastern Mineral Resources, and Western Illinois University. The many tasks involved in the planning, preparation, and conducting of the meeting were shared by the co-hosts. John Klasner of WIU served as general chairman; Klaus Schulz of the USGS arranged for the field trips and banquet speaker; John Hughes of NMU took care of local arrangements. Technical sessions and the banquet were held at the Ramada Inn on May 12 and 13. A total of 245 persons registered for the meeting. Thirty-seven oral presentations were scheduled, but two had to be cancelled because the presenters were unable to attend. Nineteen poster papers were presented and three different field trips were conducted.

New developments from seismic studies in Lake Superior by the GLIMPLE program and information from a DOSECC workshop on the Keweenaw Rift merited a special full day session on May 12, on the "Geology of the Keweenaw Rift." Also, half day sessions on May 13, were devoted to the "Geology and Mineral Deposits of Archean Rocks" and "Geology of Early Proterozoic Rocks..." respectively. Poster papers covered a variety of topics.

A total of 151 persons enrolled for field trips. A two-day trip on the "Archean Geology and Mineralization of the Marquette Greenstone Belt" conducted by T. Bornhorst of Michigan Technological University and R.A. Brozdowski and G.W. Scott of Callahan Mining Company proved very popular. The pre-meeting version of this trip filled with 50 people and the leaders kindly agreed to conduct it for 28 persons after the meeting on May 14 and 15. Twenty-nine persons participated in a special trip conducted by B. Boyum, R. Reed, and William Kangas on "The Marquette Mineral District, Mining History and Geology." Also, 44 persons enrolled in a trip on "A Structural Traverse Across a Part of the Penokean Orogen Illustrating Overthrusting in Northern Michigan" conducted by J. Klasner, P. Sims, and William Gregg. C. Gallup was a co-author of this trip but could not attend.

A total of 163 people attended the annual ILSG banquet. Don Davidson of Northern Illinois University presented the Goldich Medal to Walter White of the USGS for his many years of study of and excellent contributions to Keweenaw geology. P.F. Hoffman of the Geological Survey of Canada regaled the banquet audience with an overview of the tectonic evolution of Laurentia during early and middle Proterozoic time.

Inasmuch as the ILSG tries to encourage student participation, both in attendance at the Institute and presentation of papers, we provided financial assistance to several students and gave two best paper awards. Waiver of registration fee was given to 17 students who applied, and 13 of the 17 students were also given small (\$20-\$40) travel assistance from a special fund set aside for this purpose. An award of \$150 was presented to Bernhardt Saini-Eidukat of the Department of Geology and Geophysics, University of Minnesota-Minneapolis for the best oral presentation and a \$150 award was given to Peter Jongwaard of the University of Minnesota-Duluth for the best poster paper.

The ILSG Board of Directors luncheon meeting was held at the Ramada Inn on May 13. It was attended by C. Blackburn, B. Brown, J. Greenburg, J. Hughes, J. Kalliokoski, M.M. Kehlenbeck, J. Klasner, R. Ojakangas, R. Sage, and K. Schulz. The following items of business were discussed:

- Review of minutes from 33rd ILSG. No changes.
- Treasurer's report by J. Kalliokoski, Treasurer of the American Account, the balance in the general account as of April 2, 1987 was \$3,065.21. The Goldich Medal Funds had a balance of \$1,153.92. M.M. Kehlenbeck, Treasurer of the Canadian Account, reported a balance of \$9,664.88 as of May 12, 1988.
- R.W. Ojakangas indicated that the University of Minnesota, Duluth will host the 35th ILSG. He will serve as chairman.
- J. Klasner reported that mailing lists are out-of-date and there are names of many people on the list who are no longer affiliated with the Institute. J. Kalliokoski volunteered to update this list and forward it to the Minnesota Geological Survey where it is kept.
- M.G. Mudrey, Jr. of the Wisconsin Geological and Natural History Survey has agreed to serve on the Goldich Medal Committee. He replaces K.D. Card who finished his term on the committee.

The 34th ILSG would not have been possible without the help of many members. In particular, the success of the meeting is largely due to the numerous high quality papers presented both orally and as poster papers. Numerous members kindly agreed to serve as Session Chairs, Student Paper Judges, Goldich Committee Members, Field Trip Leaders and Board of Directors Members. Actually the Institute is a continuum, with each meeting built upon the work of previous organizers and the willingness of members to serve as hosts and organizers of future meetings.

We thank all for their help with this year's meeting.

Respectfully submitted,

J. Hughes

J. Klasner

K. Schulz

Co-hosts 34th ILSG

CALENDAR OF EVENTS

AND PROGRAM

WEDNESDAY, MAY 3

FIELD TRIPS 1, 2

8:00 a.m. Field Trip 1 (North Shore rhyolites, Minnesota) departs from Radisson, upper level. Leader: J.C. Green. Will return in evening; dinner (Dutch) en route.

8:00 a.m. Field Trip 2 (Penokean structural terranes in East-Central Minnesota) departs Radisson, lower level. Leader: T.B. Holst. Will return in time for dinner in Duluth.

6:00 p.m. to 9:00 p.m. Registration, Radisson Hotel, Duluth

7:00 p.m. to 10:00 p.m. Welcome get-together and cash bar, Radisson Hotel.

TECHNICAL PROGRAM
THURSDAY, MAY 4

Morning

8:00 a.m. Welcome and introduction

Midcontinent Rift Session
Chairs: A.B. Dickas and J.D. Miller, Jr.

- | | | |
|--|--|---|
| 8:10: | James D. Miller, Jr. | Geology of the Beaver Bay Complex, Northeastern Minnesota |
| 8:30: | Eric A. Jerde | Hypabyssal rocks of the North Shore of Lake Superior: evidence for polybaric fractionation in the Midcontinent Rift |
| 8:50: | Mark J. Severson | "Stratigraphy" and general geology of a portion of the Partridge River Intrusion, Duluth Complex, Minnesota |
| 9:10: | Karl E. Seifert | The Mineral Lake Pluton: two intrusions rather than a layered complex? |
| 9:30: | Michael G. Mudrey, Jr.
Albert B. Dickas | Fundamental unit differentiation of the middle Proterozoic Midcontinent Rift System, North America |
| 9:50: | Coffee Break | |
| 10:30: | Lyle D. McGinnis | Possible Late-Stage Thrust Faulting in a Keweenawan-Age Accommodation Zone beneath Lake Superior |
| 10:50: | J. Kalliokoski | Jacobsville Sandstone and Tectonic Activity |
| 11:10: | G. Wilson
Campbell Craddock | Mafic and clastic dikes as Keweenawan paleostress indicators in the Huron Mountains, Michigan |
| 11:30: | Thomas Suszek | Petrography and Sedimentation of the Middle Proterozoic (Keweenawan) Nonesuch Formation, Western Lake Superior Region, Midcontinent Rift Zone |
| *By title only: Susanne Th. Schmidt
John C. Green | | Metamorphic zonation in the North Shore Volcanic Group, Minnesota |
| 11:50: | Lunch Break | |

THURSDAY, MAY 4

Afternoon

1:30 to 2:30: Poster session, Viking Room

Oral Session, Mostly Economic and Quaternary

Chairs: Penelope Morton and David Groves

- | | | |
|-------|---|--|
| 2:30: | John S. Mothersill
James Fraser | The paleomagnetic record of Late Glacial
and Post Glacial sediments of Lake Superior |
| 2:50: | Gary N. Meyer | Glacial geology of Northern Minnesota:
mineral exploration applications |
| 3:10: | E.R. Koopman,
B. Dube
J.M. Franklin
K.H. Poulsen
M.R. Patterson | Deformation of the Lyon Lake massive
sulphide deposit, Wabigoon subprovince,
Northwestern Ontario, Canada |
| 3:30: | Coffee Break | |
| 3:50: | Robert J. Horton | The mining and geologic history of the
Silver Islet mine, and a conceptual ore
genesis model for the deposit |
| 4:10: | Mark L. Nebel | Metamorphism and polygenesis of ore
deposits: an example from the Madem
Lakkos PB-ZN-AG-AU deposit, Greece |
| 4:30: | Mark Smyk | Geology of the West Dead Horse Creek
diatreme-hosted rare metal occurrences,
Schreiber-Hemlo district, Ontario |
| 4:50: | End of Session | |

* * * * *

5:00-7:00 Cash bar

7:00: Banquet

Presentation of the Goldich medal to J. Kalliokoski, Michigan Technological University, by M. G. Mudrey, Jr.

Speaker: Frederick J. (Sam) Sawkins, University of Minnesota, Twin Cities
"Ore genesis models for volcano-plutonic arc systems: An agnostic view of the conventional wisdom"

FRIDAY, MAY 5

Morning

Mostly Proterozoic

Chairs: Val W. Chandler and R. W. Ojakangas

- | | | |
|--------|--|---|
| 8:00: | Gene L. LaBerge | Tectonic implications of the structure and stratigraphy of quartzites in Central and Southern Wisconsin |
| 8:20: | Bruce A. Brown | Significance of conglomerates, argillites, and dirty sandstones in the Baraboo and Waterloo quartzites of Southeastern Wisconsin |
| 8:40: | Jeffrey K. Greenberg | The Proterozoic Baraboo interval - Encore: composition data <u>et al.</u> |
| 9:00: | Lung S. Chan
Paul E. Myers | Paleomagnetic studies of Wausau Syenite Complex and Wissota Dam Mafic Dike |
| 9:20: | Terri Patton
M.K. Sood
B. Biddulph | Petrogenetic evolution of the Proterozoic Wausau igneous complex, Wisconsin |
| 9:40: | Coffee Break | |
| 10:10: | Theresa M. Bodus
William F. Kean | Preliminary paleomagnetic survey of the metasediments and metavolcanics of the Niagara Fault system in Florence County, Wisconsin |
| 10:30: | Theresa M. Bodus
Keith A. Sverdrup | Preliminary magnetic survey of the Niagara fault system in Florence, Forest, and Marinette counties, Wisconsin |
| 10:50: | Dennis J. Bebel | A ground resistivity technique for locating fracture aquifers in buried Precambrian basement, Central Wisconsin |
| 11:10: | Timothy B. Holst | The Penokean orogeny in Minnesota and upper Michigan: A comparison of the structural geology of the Michigamme and Thomson Formations |
| 11:30: | Lunch Break | |

FRIDAY, MAY 5

Afternoon

1:30 to 2:30: Poster Session, Viking Room

Oral Session, Mostly Archean

Chairs: M.A. Jirsa and Steven A. Hauck

- | | | |
|-------|---|--|
| 2:30: | David L. Southwick
Bryan Schaap
Val W. Chandler | Multiple Archean terranes in SW Minnesota-
the old gray gneiss she ain't what she used
to be |
| 2:50: | Stephen J. Schaefer | A comparison of two Archean ultramafic
pyroclastic rock units, Northwestern Ontario |
| 3:10: | James L. Welsh | Strike-slip faulting in Archean rocks in the
Virginia Horn area, N.E. Minnesota:
implications for the origin of the Virginia
Horn structure |
| 3:30: | Coffee Break | |
| 3:50: | Mark A. Jirsa | Stratigraphic and structural evolution of the
Northern Itasca metavolcanic belt, North-
Central Minnesota |
| 4:10: | Roger Kuhns | Basalt geochemistry as an indication of
tectonic environment for the central part of
the Hemlo-Heron Bay Greenstone Belt,
Ontario |
| 4:30 | William F. Read | One, possibly two, impact craters under
DePere, Wisconsin, discovered via water
well logs and drill cuttings |
| 4:50 | End of Session | |

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SATURDAY, MAY 6

FIELD TRIPS 3,4

7:00 a.m. Field Trip 3 (Mellen Complex, Wisconsin) Departs from Radisson upper level. Leaders: Karl Seifert, James Olmsted, Ken Klewin. (Vans will return to Duluth).

8:00 a.m. Field Trip 4 (Archean gold occurrences and their structural settings, Minnesota) departs from Radisson, upper level. Leaders: J. Welsh, D. England, D. Groves, E. Levy, P. Hudleston, D. Southwick, R. Bauer, W. Ulland. (Vans will return to Duluth).

POSTER PAPERS

Authors are requested to be on hand at their posters during the special poster sessions from 1:30 to 2:30 Thursday and Friday, and other times when convenient.

1. Adams, D.C., and Young, C.T., Magnetotelluric investigation of the contact between the Duluth Complex and the Animikie Basin in northeastern Minnesota.
2. Belden, J., Anderson, G., and Watkins, I., Zircons of the St. Cloud Red and Reformatory Granites.
3. Block, D.P., and Cavaleri, M.E., Petrogenesis and geochemistry of rhyolites from the Chengwatana Volcanic Group, Mid-Continent Rift System.
4. Buchheit, R.L., Malmquist, K.L., and Niebuhr, J.R., Glacial drift geochemistry for strategic minerals, Lake County, Minnesota.
5. Cannon, W.F., Schulz, K.J., Hinze, W.J., and Green, A.G., Precambrian terranes beneath northern Lake Michigan defined by seismic and gravity analysis.
6. Chandler, V.W., and Schaap, B.D., New Bouguer gravity anomaly map of Minnesota.
7. Dods, S.D., Hinze, W.J., Keating, Pierre, and Smith, J.G., Magnetic and gravity maps of Lake Huron.
8. Hinze, W.J., Ravat, D.N., McGinnis, L.D., Cannon, W.F., Milkereit, B., Sexton, J.L., and Wang, H.F., Structure of the Midcontinent Rift System in eastern Lake Superior: Preliminary results from the 8-sec reflection seismic data and gravity and magnetic anomalies.
9. Holm, D.K., and Selverstone, J., Preliminary constraints on the P-T evolution of the Penokean orogeny: east-central Minnesota.
10. Horton, R.J., and Smith, B.D., Geophysical investigations, International Falls and Roseau quadrangles, Minnesota-Ontario.
11. Jirsa, M.A., Stratigraphic and structural evolution of the Northern Itasca metavolcanic belt, north-central Minnesota.
12. Kehlenbeck, M.M., and Cheadle, S.P., Gravity survey of a portion of the Quetico and Wawa subprovinces near Thunder Bay, Ontario.

13. Kucks, R.P., Chandler, V.W., Dods, S.D., Ervin, C.P., Hood, P., McConnell, K., and Teskey, D., Potential-field anomaly maps of the Lake Superior region.
14. MacArthur, J.H., and Holst, T.B., Deformation in the Archean Knife Lake Group, Ensign Lake area of the eastern Vermilion District, northeastern Minnesota.
15. McSwiggen, P.L., Characterization of the graphite occurrences in the southern and western Penokean orogen.
16. Mudrey, M.G., McGinnis, L.D., Ervin, C.P., Nyquist, J.E., Dickas, A.B., Morey, G.B., Green, A.G., and Sexton, J.L., Structure of the Midcontinent Rift System from 8-sec reflection seismic data in western Lake Superior.
17. Peterson, J.W., Chacko, T., and Kuehner, S.M., Petrographic and microprobe study of isolated iron-formation lens near Republic, Michigan: a search for high-grade, pre-Penokean metamorphism.
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20. Setterholm, D., and Hammond, R.H., Manganese potential of the Cretaceous rocks flanking the Sioux Ridge, Minnesota and South Dakota.
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ABSTRACTS

MAGNETOTELLURIC INVESTIGATION OF THE CONTACT BETWEEN THE DULUTH COMPLEX AND ANIMIKIE BASIN IN NORTHEASTERN MINNESOTA

Adams, Donald C., Young, C. T. (Department of Geological Engineering, Geology and Geophysics, Michigan Technological University, Houghton MI, 49931)

Magnetotelluric profiling was used to investigate the resistivity contrast of the contact between the Animikie Basin and Duluth Complex in Northeastern Minnesota. Data were collected at eight sites, during June and July 1988, along a Northwest to Southeast 37 km line (Figure 1) approximately perpendicular to the contact.

Preliminary one dimensional modeling and interpretation of the data indicate that the electrical contact has the shape of a half graben sloping east and stepping to a depth of 15 km within the field area (Figure 2). The form of the contact between the Duluth Complex and the Animikie Basin agrees with the half graben interpretation of Weiblen and Morey 1980 and approximate depth to the contact determined by Frederer 1982. The Duluth Complex has an apparent resistivity of 10,000 to 60,000 ohm meters, while the Animikie Basin has apparent resistivities of 3 and 255 ohm meters and the Giants Range Granite has a apparent resistivity of 600 to 3000 ohm meters.

The field work was supported by a grant from the Minnesota geological survey.

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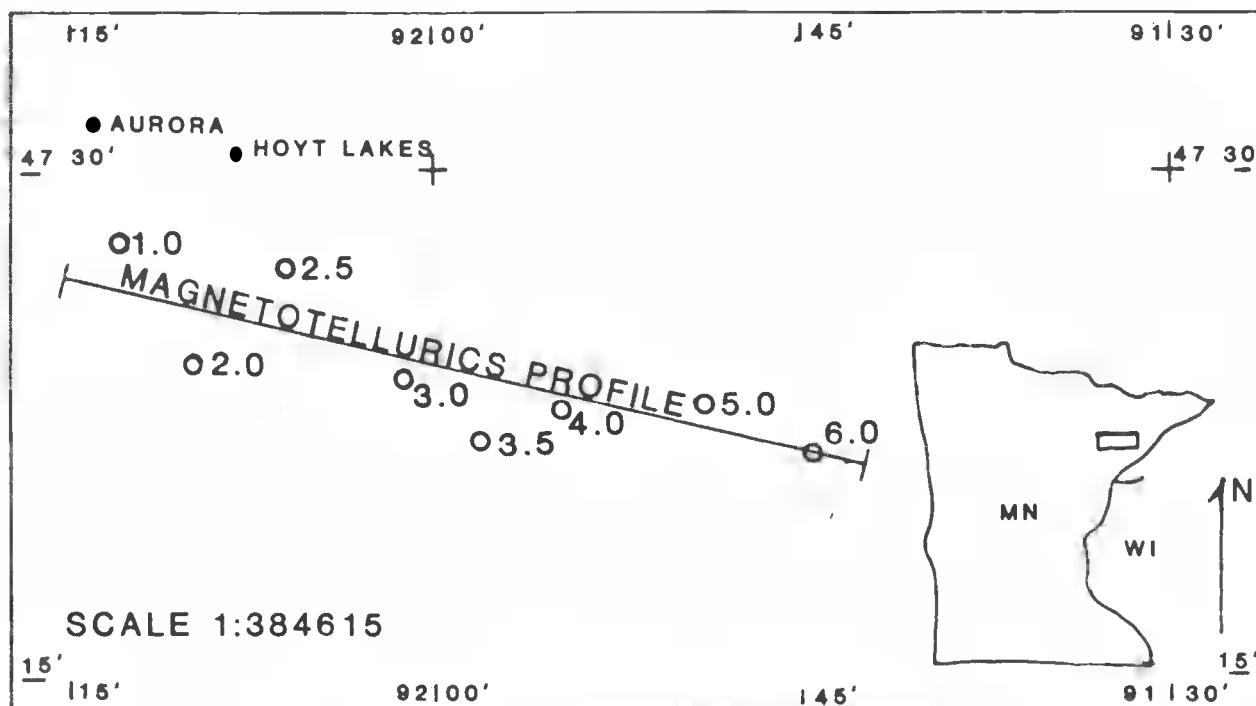


FIGURE 1 LOCATION MAP

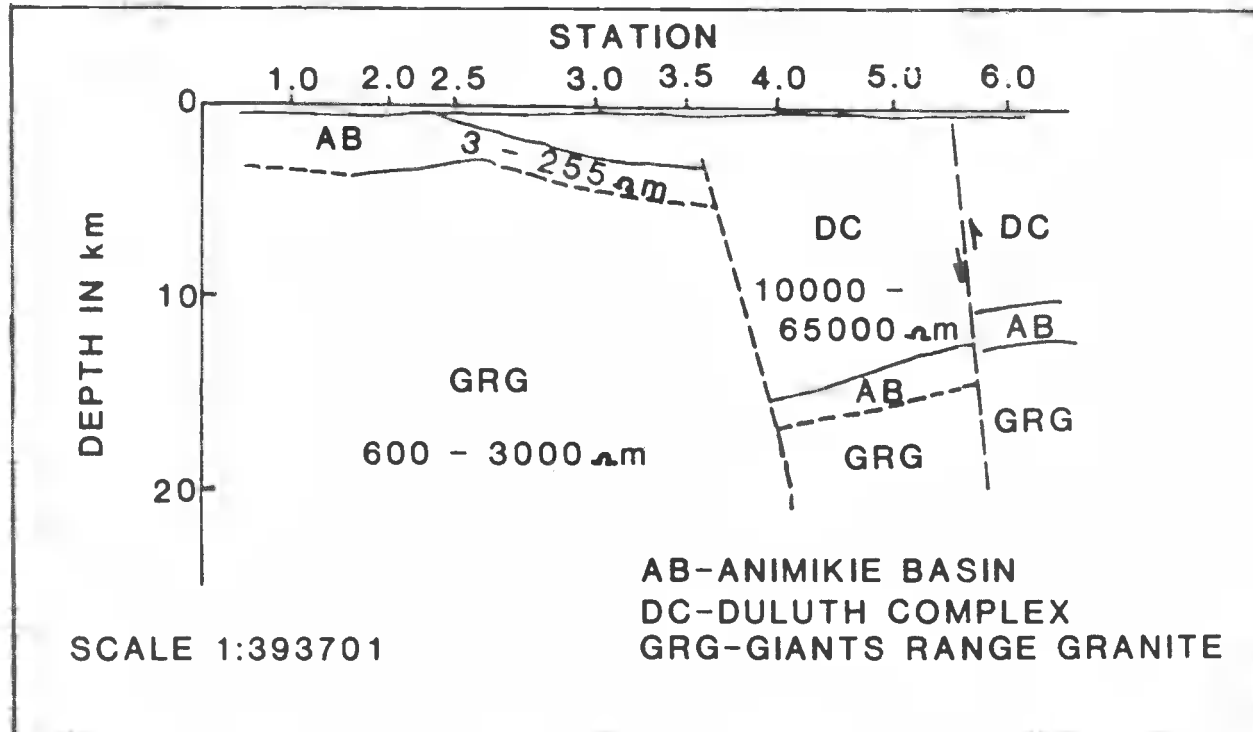


FIGURE 2 MODEL INTERPRETATION

A GROUND RESISTIVITY TECHNIQUE FOR LOCATING FRACTURE AQUIFERS IN BURIED PRECAMBRIAN BASEMENT, CENTRAL WISCONSIN

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Decreases in apparent resistivity have been recognized through comparative measurements of ground resistivity taken above and below the water table located within buried crystalline basement. These decreases have been interpreted to indicate zones of high fracture porosity and therefore increased water volume allowing for greater electrical conductivity. The survey method might provide a tool for locating water well drilling sites in crystalline basement.

A Lee array was utilized during trial surveys. Vertical electrical soundings were conducted at points along the survey traverses to adjust for surface and basement topography in establishing the depths to basement and the water table. Electrode a-spacings within the range of 4.6 - 18.3 meters were determined to provide investigation depths above and below the water table along the length of the traverses. Trial surveys were conducted near Dells of Eau Claire Park (Marathon Co.), WI and at Junction City (Portage Co.), WI.

The Dells of Eau Claire traverse crossed the contact between the Wolf River Granite and a "shear zone" in felsic volcanics. Exposures of the volcanics in the Eau Claire River display an intense fracture system. The apparent resistivity decreased below the water table within the volcanics but not the granite.

The Junction City traverse was at a water well site. Basement rock at this location is early Proterozoic argillite. An apparent resistivity decrease was noted in a narrow zone (6 - 9 meters wide) north of the wellsite and on strike with the local basement structure.

It is currently planned to further test this technique during the Spring, 1989 in conjunction with a Wisconsin Geological and Natural History Survey drilling program at Junction City, WI.

ZIRCONS OF THE ST CLOUD RED AND REFORMATORY GREY GRANITES

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Samples of both the Reformatory Grey granite and the St Cloud Red granites of central Minnesota were crushed and sieved. Using methylene iodide, zircons and other heavy minerals were separated. No zircons were found in the material larger than the 100 (149 microns) mesh sieve. Euhedral zircons that passed through the 100 mesh sieve were picked out of the heavies, mounted on a slide for microprobe analysis with the long axis of the crystal parallel to the surface of the slide, then ground to about one half their thickness. Micro photographs of individual zircons were taken using unpolarized and polarized light as well as with crossed polars.

Observations requiring little or no interpretation are:

1. zircon fragments are inside the euhedral crystals
2. non-zirconium bearing inclusions are inside the euhedral crystals
3. concentric banding is visible in all illuminations in zircons from both granites but is far more consistent in those from the St Cloud Red granite
4. microprobe data shows varying concentrations of zirconium in the crystals but no pattern has yet emerged
5. zircons from both granites are fractured but those from the Refomatory Grey show greater fracture development and subsequent mineral growth along the fractures than the St. Cloud Red
6. microprobe data of uranium concentrations is unclear at this time but work is continuing.

Observations requiring appreciable interpretation with some possible interpretations are:

1. apparent overgrowths (Sahama, 1981) on euhedral crystals occurred so the crystal is no longer euhedral or the crystal has fractured in a strange way
2. the fractures in the euhedral crystals usually do not follow cleavage planes but always appear dark in any light. The dark color may be due to zircon crystallized at a lower temperature (Caruba et al., 1985) or may be due to light not getting through because of the critical angle of illumination on the fracture. This dilemma will be resolved.
3. concentric banding shows different indices of refraction which may be due to different compositions or different lattice constants (Exarhos, 1984).

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PETROGENESIS AND GEOCHEMISTRY OF RHYOLITES FROM THE CHENGWATANA VOLCANIC GROUP, MID-CONTINENT RIFT SYSTEM

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Rhyolites form a significant volume but low (<1%) percentage of the Midcontinent Rift System (MRS). Due perhaps to their limited exposure, the rhyolites of the MRS have not been extensively studied. This study is based on chemical analyses of samples taken from two deep drill cores, V66-1 and V66-2, from Vermillion, Minnesota, about forty miles south of the Twin Cities.

The purpose of studying these cores is two fold. First, these cores represent the southernmost sampling of the MRS, and also one of the few samples of Chengwatana rhyolites. The geochemical data obtained during this study thus forms a significant addition to the data available on the MRS. Secondly, rhyolites from the MRS has not been extensively studied. Within the last ten years, a number of world rhyolite-basalt associations have been examined. Data collected on the Chengwatana rhyolites will be compared and contrasted this published data.

Core V66-2 is composed entirely of rhyolite. Core V66-1, in contrast, contains only a twenty foot section of rhyolite in a much larger amount of basalt. The chemical fingerprints of these cores also differ. Rhyolites from V66-2 are high in silica, varying from 73 to 81%. Rhyolites from V66-1 contain only about 68% SiO₂. This suggests that these rhyolites of V66-1 could have been contaminated by the surrounding basalts. Rhyolites from both V66-2 and V66-1 are peraluminous. Al₂O₃ concentrations vary from 10 to 14%, while Ca varies from .05 to 1.90% and Na₂O from .08 to 2.91%.

Based on the orthoclase-albite-quartz phase equilibria, the rhyolites of V66-2 are estimated to have formed in at temperatures less than 800 degrees celsius. Rhyolites from V66-1 have much higher albite concentrations due to probable basaltic contamination. It is possible, however that this also points towards a higher temperature of formation.

Trace element analyses show that the two cores probably have slightly different petrogenetic histories. V66-1 has much higher concentrations of strontium, phosphorus, and titanium than V66-2. Unlike the low silica levels, these differences cannot be easily explained by simple assimilation of basaltic material.

Based on the geochemistry, petrography, and field relationships, these rhyolites seem to be similar in origin to those studied elsewhere in the MRS and in other continental rift systems. The rhyolite-basalt association present here and in similar units is commonly associated with regions of thick extending crust. Based on these observations, the information collected in this study can be combined to propose a model for the origins of these rhyolites. The formation of the rhyolites begins by partial melting in the upper mantle. The magma ponds

at or near the crust/mantle interface, where it fractionates until its density is sufficiently low to allow it to rise to the surface. Rhyolites are produced by mafic magmas travelling through narrow crustal fractures which occur either along the margins of the rift system or in immature zones of where small fractures have not yet aggregated into wide conduits. Within these fracture zones, the mafic magma fractionates and the remaining material becomes contaminated with sialic crust as it rises to the surface.

PRELIMINARY PALEOMAGNETIC SURVEY OF THE METASEDIMENTS AND
METAVOLCANICS OF THE NIAGARA FAULT SYSTEM IN FLORENCE COUNTY
WISCONSIN

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Milwaukee, Department of Geosciences, Milwaukee Wisconsin 53201

Florence County in northeastern Wisconsin is a region of complex geology associated with the Niagara fault. The rocks which flank the Niagara Fault system in Florence County are metaconglomerates, metagreywackes, and metavolcanics to the north and gneisses to the south. Isotopic Nd ages of these rocks give ages of 1.80-1.88 b.y. (Barovich et al., 1989)

Paleomagnetic studies were initiated to aid in determining the relationships of emplacement and relative location of the units on either side of the fault system. Seven hand samples and twenty oriented cores were analyzed using stepwise A.F. demagnetization and thermal demagnetization to determine magnetic characteristics and magnetic directions. The gneiss samples exhibited low intensity, 10^{-6} to 10^{-7} cgs, and corresponding low magnetic susceptibilities of $2.0-20.0 \times 10^{-6}$ cgs. The rocks to the north of the fault had stronger intensities (i.e. 10^{-5}) and correspondingly strong susceptibilities $70.0-310.0 \times 10^{-6}$. The A. F. demagnetization studies indicate predominately single component magnetization after the removal of a soft overprint. Preliminary results indicate that all the rocks are reversely polarized and magnetic direction consistent with Irving's A.P.W.P. for ages of 1.81 to 1.84 b.y. for rocks north of the Niagara Fault.

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PRELIMINARY MAGNETIC SURVEY OF THE NIAGARA FAULT SYSTEM IN
FLORENCE, FOREST, AND MARINETTE COUNTIES, WISCONSIN

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Milwaukee, Department of Geosciences, Milwaukee

The Niagara Fault indicated on the Wisconsin State Bedrock Map extends from northwestern Wisconsin across the state to northeastern Wisconsin. This study concentrates on the northeastern portion of the fault in Florence, Forest, and Marinette counties, Wisconsin. Total field magnetic data was obtained at 0.1 mile spacing using a proton precession magnetometer in two N-S profiles across the Niagara Fault in Florence county (Fig. 1). These profiles were positioned to cross the Niagara fault and related faults as they are plotted on the Northeastern Bedrock Geology Map (1984). Expected locations of the faults crossed by the profiles are indicated in the figure by arrows. The data is characterized by relatively low level, constant values for roughly twelve miles south of the fault and several high amplitude anomalies to the north suggesting a fundamental change in the geology between these two areas. Measurements of susceptibility have been made on seventeen samples from five sites in the study area to assist in modeling. The values range from 4.0-308.0 $\times 10^{-6}$ cgs. Preliminary modeling of the data has begun, and results of the modeling will be presented.

MAGNETIC PROFILE

a file b:Hwynu
 netic data HIGH is 608000.0.
 netic data LOW is 58020.7.
 l scale deflection is 3000.0 gammas.

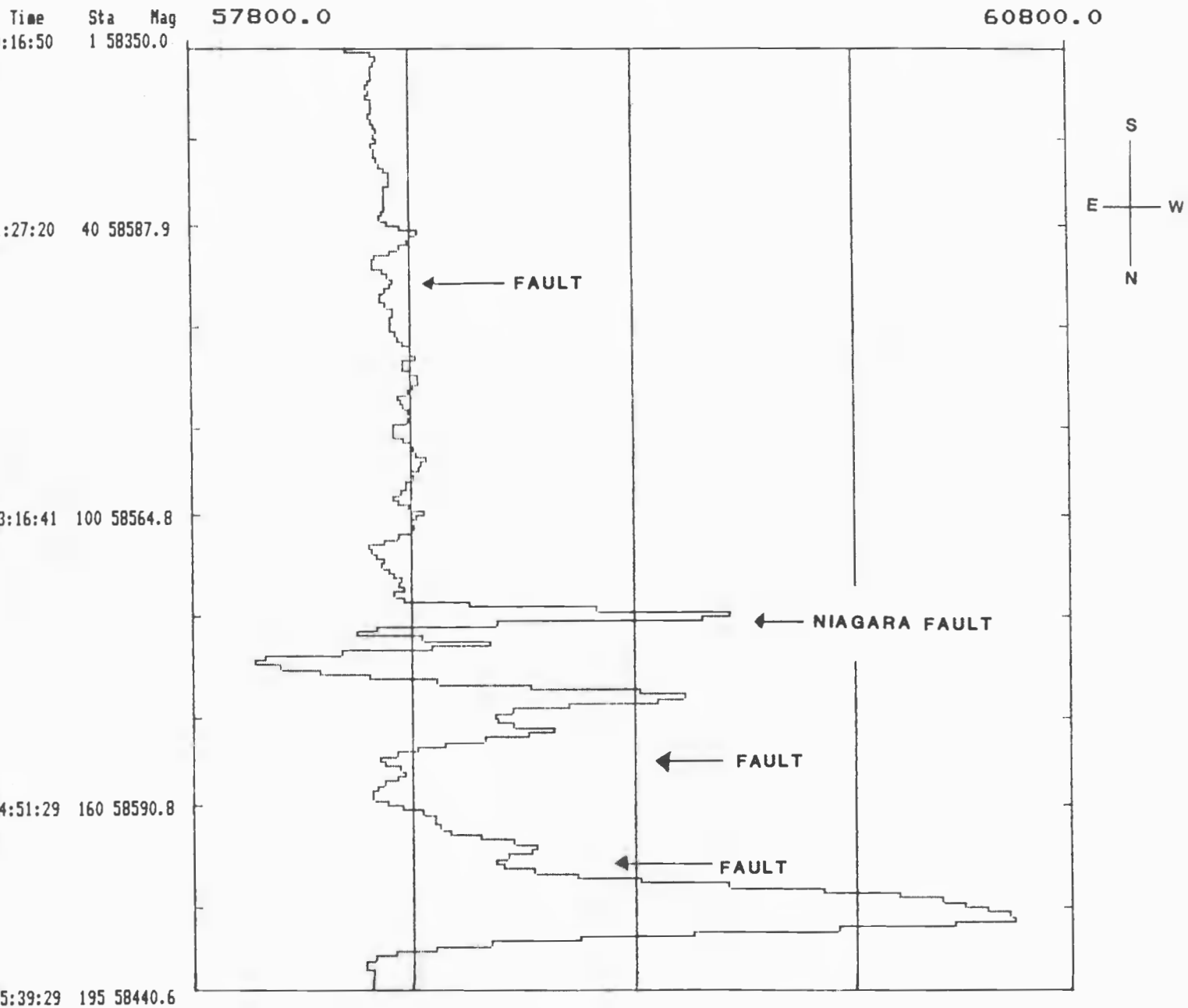


Figure 1. Magnetic survey profile along Highway N and U in Florence county.

SIGNIFICANCE OF CONGLOMERATES, ARGILLITES, AND
DIRTY SANDSTONES IN THE BARABOO AND WATERLOO QUARTZITES
OF SOUTHEASTERN WISCONSIN

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Recent studies of the Baraboo and Waterloo quartzites of southeastern Wisconsin suggest that both contain abundant beds of poorly sorted pebble conglomerate, and that both are anomalously rich in clay matrix when compared to other quartzites of the "Baraboo interval."

A study of the Baraboo quartzite by Henry (1975) identified a lower unit, 60 to 200 m thick, composed of predominantly lenticular pebbly beds up to 0.6 m thick. Milky quartz pebbles dominate, with lesser amounts of chert, hematitic chert, siltstone, single grain and polycrystalline clear quartz, and quartzite. No clearly identifiable rhyolite pebbles were reported by Henry, although he suggested that some fine-grained silicious pebbles and scattered embayed quartz grains might be volcanic materials. Pebble beds become less abundant upwards, and sandy beds contain up to 10 to 20% clay matrix (pyrophyllite and kaolinite).

The Waterloo Quartzite shows a similar fining-upward tendency, with lenticular pebble conglomerates and matrix rich (sericite) sandstone common in the lower part of the section. Pebble conglomerates are thicker (up to 2 m) and more abundant at Waterloo, but pebble lithologies are similar.

The lithologic sequence at Waterloo and Baraboo are nearly identical, and may be directly correlatable. Both fine upwards from pebble conglomerates to sandstone. Drilling records suggest a slate unit overlying Waterloo to the east, which may correspond to the Seely slate at Baraboo. Ferruginous, silicious slate drilled in a well at Watertown may be equivalent to Freedom Formation. A well in Monona, on the east side of Madison, encountered pebble conglomerate similar to the lower part of the section at Baraboo and Waterloo. This rock contains more varied pebble types, including possible volcanic material.

Primary sedimentary structures in the Baraboo and Waterloo Quartzites suggest distal alluvial to braided fluvial depositional environment (Henry, 1975). Consistent southward paleocurrents reported by Dott and Dalziel (1972) indicate fluvial transport to the south. Pebble conglomerate lenses are suggestive of bars or possibly sheetflow deposits. Thin argillite beds may represent overbank deposits.

The scarcity of rhyolite pebbles is puzzling if the source terrane for the quartzites was the 1760 ma. granite rhyolite terrane to the north. A possible explanation is that the rhyolite was eroded under severe weathering conditions, contributing only the quartz and the kaolinite clays now seen in the matrix. Alternatively, rhyolite debris may have degraded during diagenesis to form the

ubiquitous matrix. Abundant metamorphic quartz and the hematitic cherts suggest that other sediment sources contributed as well. The Barron Quartzite (Rozacky, 1987) and the Sioux quartzite (Ojakangas and Weber, 1984) apparently contain significantly less pebble conglomerate and less matrix, probably reflecting very different source terranes and transport history.

Samples from deep wells and unpublished geophysical data suggest that the quartzites of Baraboo and Waterloo are continuous over an extensive area of southeastern Wisconsin.

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GLACIAL DRIFT GEOCHEMISTRY FOR STRATEGIC MINERALS, LAKE COUNTY, MINNESOTA

DNR Project #262

Funded by Minnesota Future Resources Commission

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Minnesota Department of Natural Resources
Division of Minerals, Hibbing, MN 55746

ABSTRACT

This mineral diversification investigation is funded by the Minnesota Legislature for the July 1, 1987 through June 30, 1989 biennium. It is a pilot study of regional geochemical survey methods for identification of non-ferrous, strategic minerals in vegetation, soils and surface, and glacial deposits. Analytical results can indicate the presence of metallic mineral deposits in bedrock or outline geochemically anomalous locations suitable for detailed followup studies or mineral exploration.

The project area includes T.59-61N., R.7-11W., in Lake County, excluding lands lying within the BWCA. This 400 square mile area is underlain by the Duluth Complex and North Shore Volcanics which may host potentially economic quantities of platinum, PGE's, chrome, cobalt, titanium, base metals, gold and silver. Outcrop is minimal with surface cover being varying thicknesses of glacial deposits of the Rainy and Superior lobes.

Approximately 1200 locations, statistically distributed according to existing road access, are being sampled during the 1988 field season. Samples are normally obtained at 1/4-mile intervals with overburden samples being obtained from 4-inch diameter holes augered to a depth of 5 feet.

Sampled media include glacial overburden, humus, A and B soil horizons and vegetation of available species including alder, balsam fir, jack pine, and black and white spruce. The heavy mineral concentrate and -2 micron (clay) fraction are assayed from the glacial overburden samples.

Samples are being analyzed for Pt, Pd, Cr, Au, Ag, Co, Y, TiO₂, Cu, Ni, Pb, Zn, Bi, Sb, Se, Te, As, MgO, Fe₂O₃.

Results of this investigation are available to the public on open file with the Minnesota Department of Natural Resources, Division of Minerals, in Hibbing, Minnesota. A summary report will be issued by DNR-Minerals after July 1, 1989.

Precambrian Terranes beneath Northern Lake Michigan
Defined by Seismic and Gravity Analysis

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A seismic reflection profile along a line about 290 km long from near the Straits of Mackinac to near Manitowoc, Wisconsin, was collected during the 1986 GLIMPCE seismic experiment in northern and western Lake Michigan. Data were recorded for 20 seconds to provide information on the full thickness of the crust and the uppermost mantle.

The line crosses several Precambrian terranes that are exposed and well studied about 100 km to the west in northern Michigan and Wisconsin. These terranes can be projected onto the seismic line (Figure 1) with the aid of regional gravity and magnetic maps. A gravity model along the seismic profile further constrains the geologic interpretation.

At the north end of the line, the western half of the Midcontinent Rift basin is shown by strong continuous reflectors from basalt flows. Reflectors can be traced to about 20 km depth. The rift formed at 1.1 Ga in basement rocks believed to be mostly Archean gneisses. Very high densities inferred for the lower crust suggest abundant rift-related mafic intrusive rocks. The Archean gneisses appear on the seismic record as richly reflective material dominated by a multitude of short, subhorizontal reflections. A dense and strongly reflective lower crustal layer, as much as 20 km thick, is probably granulitic gneiss. The Moho, generally located at the rather sharp change from strongly reflective lower crust to acoustically transparent mantle, dips gently northward toward the Midcontinent Rift, probably as a result of flexural loading, and reaches a depth of about 55 km beneath the rift.

Farther south, the Niagara fault can be projected onto the profile from the fault's exposure in northern Michigan and Wisconsin, where it is a steeply dipping fault zone that represents the suture between the Archean craton on the north and an Early Proterozoic volcanic arc, the Wisconsin magmatic terrane. No reflections can be directly ascribed to the Niagara fault, but its general location is marked by a change in reflective character of the crust. The arc terrane has abundant subhorizontal reflections throughout the crust, with the exception of a few nearly transparent areas that we interpret as granitic intrusive rocks. Gravity analysis indicates that the terrane is dominated by low density rocks, probably a combination of calc-alkaline volcanics and related granitoid rocks. An intensely reflective layer about 6 km thick at the base of the arc terrane appears to have unusually high density, and we interpret it as granulite. The Moho is an essentially flat surface about 40 km deep beneath the arc terrane.

The southern third of the line contains an intensely reflective lower crustal layer above a largely transparent mantle. The reflective crust is tentatively identified as Archean gneisses accreted to the southern margin of the arc terrane during the Penokean orogeny about 1,850 million years ago. Approximately the lower half of the crust is especially reflective and has high density. As with the Archean crust to the north, we interpret this as lower crustal granulitic gneiss. The Moho dips gently northward beneath this terrane and appears to have an abrupt offset near the contact with the Wisconsin Magmatic terrane. This unusual Moho offset may be a vestige of deeply subducted crust.

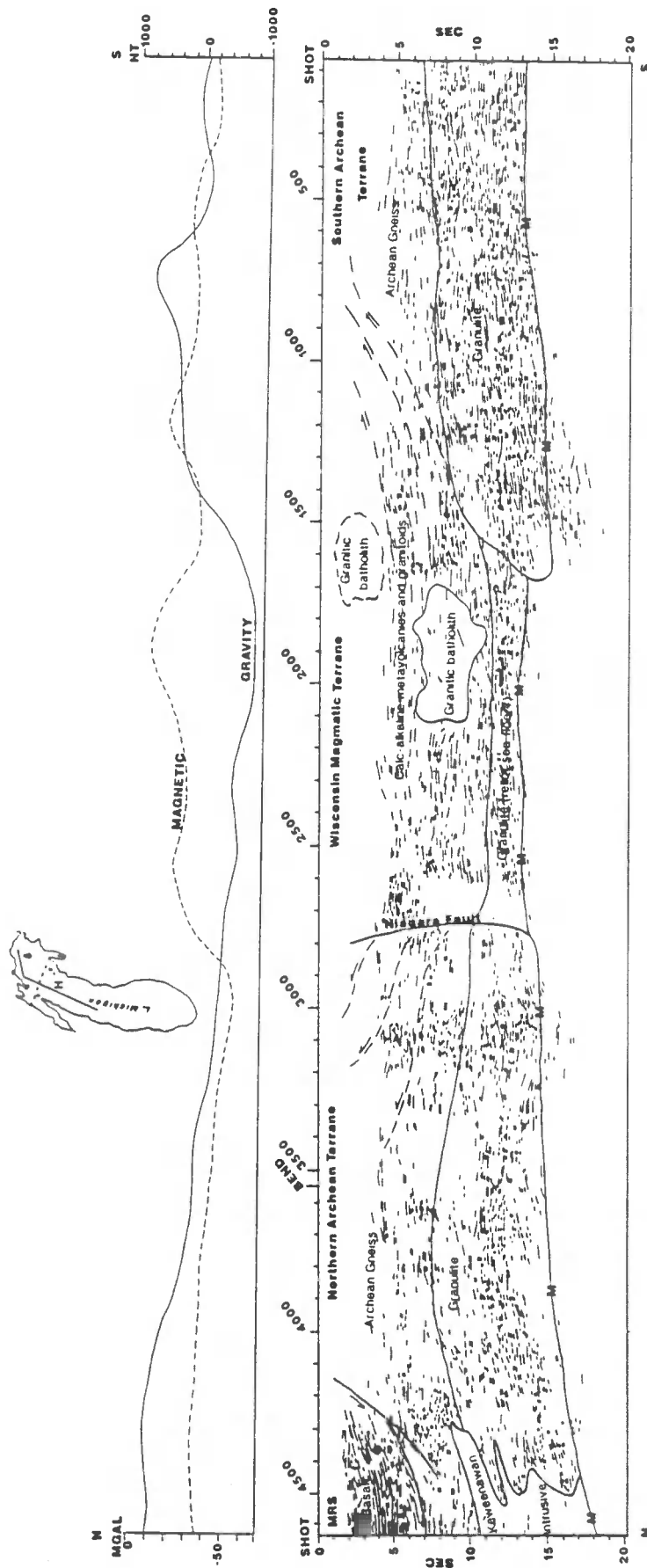


Figure 1. Schematic interpretation of line drawing of GLIMPCE line H in northern Lake Michigan and inferred subsurface terranes interpreted from seismic and gravity analysis. Dashed thrust faults are schematic and consistent with tectonic models for on-land geology west of the line. MRS = Midcontinent rift system. M = Moho. Shot spacing is 62.5 m. Horizontal and vertical scales are equal for velocity of 6 km/s.

Paleomagnetic Studies of Wausau Syenite Complex and
Wissota Dam Mafic Dike

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Remanent magnetism of the Wausau syenite complex in Marathon County, Wisconsin, shows a westerly declination and yields a virtual geomagnetic pole similar to the 1.1 Ga paleomagnetic pole of the North American craton [Zich et al., 1986]. In addition, the paleomagnetic data reveal multiple magnetic components. The magnetization history of the Wausau syenite can be worked out by comparing the magnetic results with paleomagnetic directions from mafic dike swarms in the Southern Superior Province and a mafic dike at Wissota Dam in Chippewa Falls, Wisconsin.

The Wausau syenite complex of Central Wisconsin represents a post-Penokean, anorogenic intrusion which is probably coeval with the Wolf River granite [LaBerge and Myers, 1984]. The granite and syenite were intruded by a swarm of east-northeast striking mafic dikes. Rubidium-strontium measurements of two samples from Wausau yielded a minimum age of 1.52 Ga [Van Schmus et al., 1975]. Since the Proterozoic polar wander curve for North America Craton contains a gap between 1.60 Ga and 1.45 Ga, a paleomagnetic study of the Wausau syenite may help to fill the gap in the polar wander path.

The Wausau syenite was sampled at four locations and demagnetized by both alternating field and thermal techniques. Kirschvink's [1980] procedure for vectorial analysis of paleomagnetic data was used to extract linear segments from the results of measurements. A linear segment is defined here as a set of three or more consecutive points in a demagnetization curve that show less than 10° angular deviation about their mean direction. Each linear segment is considered as a magnetic component. In Fig. 1, the magnetic components of all samples are plotted and contoured on an equal-area projection.

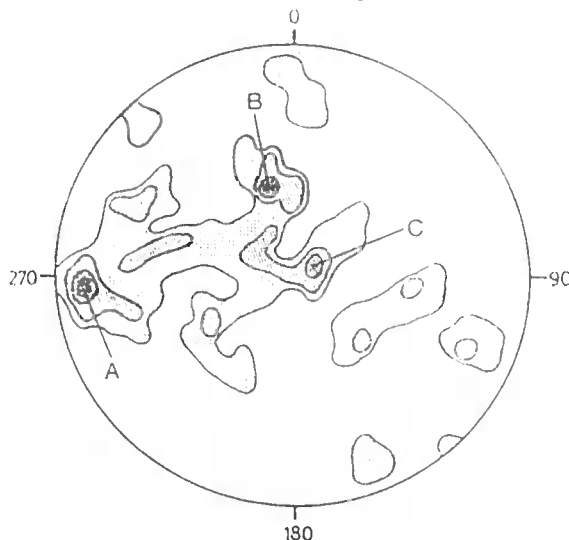


Fig. 1 Contoured distribution of magnetic components in Wausau syenite samples at 1 per 1% area.

We define a magnetic component cluster as a direction that contains three or more components per 1% of stereonet area. Magnetic components from the Wausau syenite complex form three magnetic component clusters (Fig. 1), the most prominent of which (A) shows a direction of $D=266^\circ$, $I=14^\circ$ and a vgp at $\text{lat}=2^\circ$, $\text{long}=172^\circ\text{W}$. A second cluster (B) has a direction of $D=347^\circ$, $I=57^\circ$ and a vgp at $\text{lat}=77^\circ$, $\text{long}=147^\circ\text{E}$. This magnetic component cluster probably represents a present-field overprint because of the high vgp latitude. A third magnetic component cluster (C) shows a direction $D=62^\circ$, $I=83^\circ$ and gives a vgp at $\text{lat}=50^\circ$ and $\text{long}=71^\circ\text{W}$. This vgp lies on course with the

extension of the middle Proterozoic polar wander path of the North America Craton and probably represents the primary component acquired at the time of intrusion. The magnetic component A was likely acquired during the Keweenaw magmatic event. Ilmenite in the syenite is probably an oxidation of a titanomagnetite. Previous paleomagnetic studies of mafic dikes in the Southern Superior Province have also yielded virtual geomagnetic poles that lie within the polar wander path (Logan Loop) for North America during Keweenaw times 1.2-1.0 Ga [Green et al., 1987].

The 50 m mafic dike below Wissota Dam in Chippewa Falls represents a shallow intrusion into foliated trondjemite of late-middle Proterozoic age. Although the dike is symmetrically zoned with regard to composition and grain size, numerous inclusions of very coarse plagioclase (An^{55}) and norite are confined to a 2-m zone along the north wall. The 34-m core of the dike consists of ilmenite-bearing clinopyroxene-olivine gabbro. Grain size diminishes outward to a highly altered aphanitic clinopyroxene basalt. From the center outward the dike is symmetrically altered, first to epidote replacements of plagioclase, then to chlorite-epidote replacements of pyroxene accompanied by conversion of olivine to talc and serpentine. Biotite, possibly as a replacement of chlorite, appears about 6 meters from each contact. The iron-titanium mineral along the dike margin is a titanomagnetite highly altered to hematite.

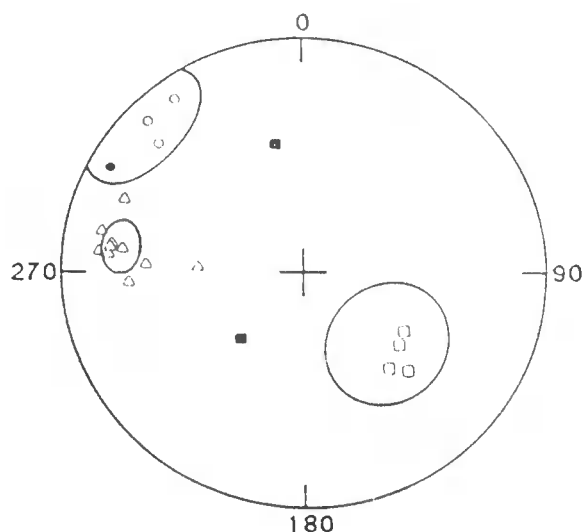


Fig. 2 Nrm directions in Wissota Dam mafic dike and alpha-95 confidence circles (triangles : sites 1 and 2, circles: site 3, squares : site 4).

Oriented core samples were collected at four distances from the northern dike margin: 10 cm, 1m, 7m, and 25m. The samples were demagnetized with alternating field technique and linear segments were determined by vectorial analysis. As shown in Fig. 2, the remanent magnetism directions of the center sites differ significantly from that of the marginal sites. We interpret such different directions as a result of different magnetic mineralogy. The differentiation of the dike rock may signify difference in crystallization temperature, with magnetite formed earlier along the dike margin, and the ilmenite of the core crystallized later at lower temperature. The nrm of the finer-grained marginal rocks, therefore, may represent an early acquisition at the time of intrusion.

Considering the remanent magnetism of the marginal zone of the dike an early acquisition, the two marginal sites yield a vgp at lat=-2.2°, long=163.87°E. As shown in Fig. 3, the vgp falls near the polar wander path at 1.0 Ga. A comparison of the vgp coordinates with previous results obtained from dike

swarms in the Southern Superior Province suggests a relatively younger intrusion age of the dike at Wissota Dam.

Our preliminary inferences from the paleomagnetic studies of the Wausau syenite and the mafic dike at Wissota Dam may be summarized as follows: first, the three magnetic components present in the Wausau syenite represent (1) a primary component acquired at the time of intrusion, (2) a present field overprint, and (3) a remagnetization during the Keweenaw magmatic event. Secondly, the remanent magnetism directions in the mafic dike near Wissota Dam reflect different magnetic mineralogy of the dike rocks. Thirdly, the mafic dike could have been emplaced later than the mafic dike swarms in the Southern Superior Province.

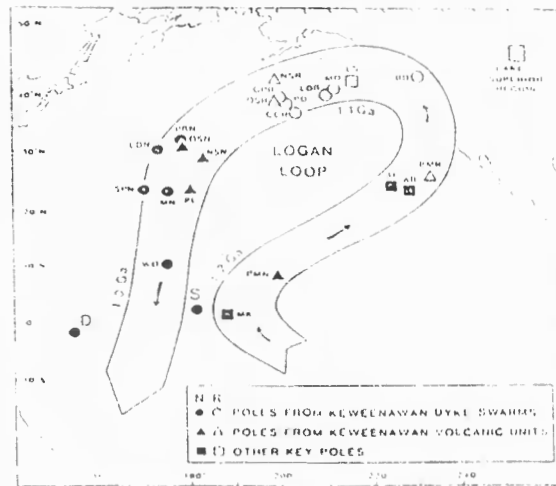


Fig. 3 Comparison of vgps of Wausau syenite (S) and Wissota Dam mafic dike (D) with Southern Superior paleomagnetic data summarized by Green et al. [1987].

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NEW BOUGUER GRAVITY ANOMALY MAP OF MINNESOTA

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The Minnesota Geological Survey is preparing a new Bouguer gravity anomaly map of Minnesota (scale 1:500,000), marking the completion of a state-wide gravity surveying program that began over 20 years ago with the goal to acquire data at a spacing of 1.6 to 3.2 km. This program was initiated by P.K. Sims, former director of the MGS, and the first surveying was conducted between 1965-1969 under supervision of R.J. Ikola. In the following years surveying continued under supervision of G.B. Morey, G.A. Durfee, L.D. McGinnis, C.P. Ervin, R.J. Horton, and V.W. Chandler. The data were published as a series of 1:250,000-scale sheets between 1968 and 1987. A few older data sets were incorporated that were determined to be suitably accurate. Over the last several years additional coverage has been acquired within several of the published sheets, and the gravity database, which had numerous errors and omissions, has been carefully edited and corrected. The final version contains 55,860 gravity stations, equating to an average station spacing of about 2.4 km state wide. The edited data were reduced using a density of 2.67 grams per cubic centimeter and the 1967 gravity formula (International Association of Geodesy, 1967).

The new state map is contoured at a 1-milligal interval and is based on gridded data generated at a 1.5-km interval using minimum curvature. This map will be a major improvement over the previously published state map (Craddock and others, 1970), which was primarily based on stations spaced 10 km apart and used a 10-milligal contour interval. The gridded data can also be used in a wide variety of computer enhancement options, including second vertical derivative.

The high resolution of the new state map presents a greatly improved perspective on Archean and Proterozoic structures. In the Archean greenstone-granite terrane of northern Minnesota, northeast-striking gravity highs and lows, which differ in amplitude by 30-60 milligals, delineate the metavolcanic and granitic belts, respectively. Second vertical derivative enhancement of these data is extremely useful for picking contacts, which are commonly traced by the zero contour, and for recognizing subunits within the granitic and metavolcanic belts. In the Archean gneiss terrane of southwestern Minnesota, gravity highs and lows delineate mafic and felsic units, respectively, and two northwest-striking lineaments appear to reflect major fault zones that divide the terrane into three distinct blocks. Over the Early Proterozoic Penokean fold-and-thrust belt in east-central Minnesota, an arcuate belt of gravity anomalies extends through southwestern Carlton County, central Crow Wing County, and into north-central Stearns County; it is believed to trace the Serpent Lake structural discontinuity of Southwick and others (1988). Southeast of this major structural front, a somewhat irregular distribution of gravity highs and lows characterizes a magmatic terrane composed of Penokean intrusions of varying compositions and gneissic rocks. In the Middle Proterozoic Midcontinent rift system, the gravity data delineate the Douglas and Pine faults along the northwestern margin of the St. Croix horst and define several units within the Duluth Complex. Thus the new state map and its

digital data base should be extremely useful for geologic studies and mineral exploration for many years into the future.

The gravity surveying program has been funded by the Minnesota Iron Range Resources and Rehabilitation Board, the Minnesota Department of Natural Resources, the Minnesota Future Resources Commission (formerly the Legislative Commission on Minnesota Resources), and the U.S. Geological Survey. Publication of the state map is being funded by the Minnesota Future Resources Commission.

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MAGNETIC AND GRAVITY ANOMALY MAPS OF THE LAKE HURON REGION

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A 1:1 million scale aeromagnetic compilation of Lake Huron and surrounding areas integrates new surveys over Lake Huron, Georgian Bay, and land areas east of the lake with older aeromagnetic coverage in Michigan and Ontario. Existing gravity data were compiled at the same scale.

A variety of derived maps have been prepared from these data sets to emphasize particular attributes of the anomaly fields and facilitate the geologic interpretation of the potential field data. In concert with other geophysical data and geologic information from the Lake Huron environs, these maps are useful in delineating basement structural/petrologic provinces of the lake. Noteworthy is the magnetic high of the Grenville Front tectonic zone that aids in refining the position of the Grenville Front beneath the Michigan Basin.

THE PROTEROZOIC BARABOO INTERVAL - ENCORE:
COMPOSITION DATA ET AL

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C.R. Van Hise would surely be pleased to witness the sustained intrigue concerning the Baraboo quartzite and other possibly correlative metasedimentary units in the southern Lake Superior region. Although limited by relatively few scattered outcrops, we continue to employ every type of analysis in deciphering the history of the "Baraboo Interval." It has recently been suggested (LaBerge and Klasner 1988) that two different sequences of Baraboo-type quartzitic rocks can be distinguished (old idea revisited) and that the older sequence represents some type of clastic wedge eroded from Archean basement and thrust southward during ca. 1850 Ma. arc-continent collision in central Wisconsin. These interpretations depend on indirect stratigraphic and structural relationships.

Until sufficient age data become available, the origin of the metasedimentary rocks is best indicated by their modal and chemical composition. Compositional criteria are now primary factors in the determination of magmatic origins, ascertaining both source material and tectonic environment. The interpretation of compositional data for metasedimentary rocks can likewise be a relatively unambiguous determinant of provenance and depositional environment.

Tectonic-sedimentation interpretations of the Baraboo Interval (see Greenberg and Brown 1984) were reassessed through the integration of chemical analyses from over twenty outcrop areas with other available data. The three major depositional hypotheses from Greenberg and Brown (1984) include: A) a near-continuous clastic shelf transgression; B) multiple sequences separated by major unconformities, and C) complex epicratonic environment, basin and range-type fault-bound basins. The last of these was previously preferred, with the concurrence of Southwick and others (1986) concerning the origin of the Baraboo Interval Sioux quartzite in Minnesota.

Modal/chemical characteristics indicate that the Baraboo interval rocks are of variable provenance. The typical modal constitution of the coarser lithologies bespeaks of variable to mature weathering and erosion and predominantly felsic igneous or reworked sedimentary sources. Major and trace element contents indicate that separate exposures bear evidence of their own restricted source areas. For example, K_2O , MgO , Nb , and Zr versus SiO_2 plots display little or no clustering of samples, regardless of grain size or silica content. Rare earth abundances of many arenitic and pelitic samples closely mirror the REE patterns of nearby felsic plutons and extrusives of both Penokean and post-Penokean 1760 Ma. age. Archean or mafic terrane components are generally absent. Eroded Archean rocks of central or northern Wisconsin are an unlikely source for most of the Baraboo interval sediments. In all instances the plots of data on tectonic discriminant diagrams (such as $TiO_2 - Fe_2O_3 + MgO$ and $K_2O/Na_2O - Fe_2O_3 + MgO$, Bhatia, 1983; $Hf-Th-Co$, Taylor and McLennan, 1985; $SiO_2/Al_2O_3 - K_2O/Na_2O$, Roser and Korsch, 1987) conforms with cratonic, passive margin, or rift environments. There is no indication of orogenic associations (subduction, collision, etc.).

As a test of hypotheses, the composition of Baraboo interval exposures further supports model C (above) of Greenberg and Brown (1984). The possibility of multiple sequences (model B) in combination with model C is also compatible with the data. However, the most compelling implication of Baraboo interval study continues to be that the sedimentary - magmatic association represents the product of anorogenic processes. Such is also the case with many other Proterozoic associations (Athabasca - Thelon, Gowler, Jotnian, Roraima, Hammamat). The most reasonable age for most Baraboo interval deposition remains near 1760 Ma. Similar though less evident episodes of sedimentation could also be associated with earlier or later post-orogenic magmatism in Wisconsin. The Jotnian clastics of Scandinavia were deposited in multiple generations separated in time by pulses of felsic to bimodal anorogenic magmatism (Lundqvist 1979). Without extensive and accurate isotopic age data, the Jotnian exposures might appear to have all been contemporaneous.

Tectonism responsible for deformation of the Baraboo interval outcrops is not easily comprehended. Some southward thrusting is a reasonable interpretation, but it would likely have been in response to anorogenic (tensional?) influences, not orogenic.

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Structure of the Midcontinent Rift System in Eastern Lake Superior: Preliminary Results from 8-sec Reflection Seismic Data and Gravity and Magnetic Anomalies

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Seismic reflection, gravity, and magnetic anomaly data confirm GLIMPCE interpretations of the structural style of the Midcontinent Rift System in eastern Lake Superior. In contrast to interpretations made prior to seismic reflection studies, eastern Lake Superior is shown to be underlain by a relatively symmetric folded graben consisting of a thick (>15 km) basal layer of mafic volcanic rocks overlain by clastic sedimentary rocks reaching thicknesses of the order of 7.5 km. A seismic line ≈ 20 km from the southern shoreline of the lake shows that the graben continues from the center of the lake into the eastern Northern Peninsula of Michigan with only minor attenuation. The western margin of the graben occurs in the vicinity of Grand Island. No evidence of volcanic rocks are seen west of the graben near the southern shoreline. A broad arch with a relief of ≈ 3 km occurs off Deer Park, MI at $\approx 47^\circ\text{N}$, $85^\circ 45'\text{W}$. The axis of the graben is interpreted to lie to the west of the arch in the vicinity of Au Sable Point, MI. Thick (≈ 7 km) Keweenawan sedimentary rocks overlying volcanic rocks occur east of the arch associated with a gravity minimum at the end of the seismic line.

Seismic reflection data are obtained under license from Grant Norpac and studies are supported in part by the U.S. Dept. of Energy, Office of Energy Research under contract W-31-109-Eng-38.

Preliminary constraints on the P-T evolution of the Penokean orogeny: east-central Minnesota.

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New and improved petrologic techniques have increased our understanding of regional metamorphism during collision and allow important constraints to be made on plate tectonic models. Detailed petrologic studies of orogenic belts have been successful in using the metamorphic signature of a terrane to evaluate the tectonic development of a region and to quantify the pressure-temperature evolution during orogeny. Such a study is here applied to rocks which have been multiply deformed and metamorphosed during the Penokean orogeny. This technique is particularly useful in east-central Minnesota where conventional geologic mapping is highly limited by very poor exposure.

The Penokean orogeny was a major early Proterozoic (1875-1825 Ma) tectonic event in the Great Lakes region. Holm and others (1988) have proposed a plate-tectonic model for the Penokean orogeny based on strain analysis, conditions of metamorphism and structural geology. Their model incorporates continental rifting followed by footwall deformation associated with oblique continental convergence (A-type subduction) and imbrication of the footwall onto the hangingwall during uplift associated with continued convergence. Early Proterozoic supracrustal rocks (Denham and Thomson Formations) have been multiply deformed and highly metamorphosed during the Penokean orogeny, with metamorphic grade increasing from north to south. Petrographic analysis of these rocks indicates progressive metamorphism during an early phase of deformation that produced synkinematic (rotated) garnet porphyroblasts and a well-developed schistosity. The thermal peak of metamorphism, however, occurred after a later phase of deformation, as indicated by staurolite porphyroblasts overprinting both the primary schistosity and a younger crenulation cleavage.

We have collected samples across an approximately 15 km NE-SW transect in garnet and staurolite grade rocks of the Thomson Formation. Temperature and pressure estimates of final equilibration were obtained using the thermobarometric techniques (on rim analyses) of Ferry and Spear (1978) and Ghent and Stout (1981) as modified by Hodges and Crowley (1985). The northern most samples of garnet grade rocks (Moose Lake area) give final equilibration temperatures of 440-500° C. Farther south in garnet grade rocks final equilibration temperatures of 470-520° C and a pressure of around 6 kb are obtained. Staurolite grade Thomson Formation samples (just north of the Denham Formation) give final equilibration temperatures of 520-590° C and a pressure of around 7 kb.

Staurolite grade Thomson Formation contains the assemblage staurolite+garnet+plagioclase+chlorite+muscovite+biotite+quartz. Garnet shows a systematic compositional zoning of increasing spessartine and grossular content and decreasing almandine content from rim to core. Inclusion-rich (quartz) garnet cores surrounded by haloes of inclusion-free garnet suggest two stages of

garnet growth. Microprobe analyses of plagioclase in contact with garnet indicates two coexisting plagioclase compositions (albite, $X_{An}=0-0.05$ and oligoclase, $X_{An}=0.23-0.28$). An attempt was made to model changes in P and T using the Gibbs method on garnet rim and core analyses. Assuming oligoclase as the plagioclase phase in equilibrium with garnet and using almandine and grossular as monitors, Gibbs method modelling on two different garnets suggests no change in temperature and an increase in pressure of 1.5-2.0 kb during garnet growth. This result is consistent with the model of Holm and others (1988) in which early formed structures and progressive metamorphism are considered related to footwall deformation during southward-directed subduction. A similar isothermal compression path was obtained by Crawford and Mark (1982) and Spear and Selverstone (1983) on samples from the lower plate of a thrust nappe. Our results are problematic however as the modelling predicts a large change in anorthite composition (+0.30) that is not observed in our samples.

Two stage modelling using compositional changes ($X_{alm,spess}$) in the inclusion-rich and inclusion-free areas of garnet and including staurolite as a phase only for the second stage of garnet growth again gives no temperature change and only a slight decrease in pressure during garnet growth (60 bars). This result, if real, suggests rapid growth of garnet and high rates of strain. Rapid growth rates reported in the literature range from 0.6-1.5 mm/Ma (Christensen and others, 1988; Staude and Selverstone, 1988). Using these growth rates, the amount of rotation recorded by the garnet during its growth implies a minimum shear strain rate of $3-7 \cdot 10^{-14}$ /s (not considering bulk strain in the matrix). Assuming a slower average growth rate of 0.1 mm/Ma gives a minimum shear strain rate of $1.4 \cdot 10^{-14}$ /s.

We emphasize that the results presented here are preliminary and much further work is needed to quantify pressures, temperatures, strain rates, etc. associated with the deformational history of this area. However, these results indicate that, with further work, such constraints can be obtained and will greatly enhance our understanding of crustal deformation as well as improve our knowledge of plate-tectonic processes back into the Precambrian era.

This research has been supported by a Sigma Xi grant-in-aid of research to Daniel K. Holm and by NSF grant EAR86-58145 to Jane Selverstone.

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**THE PENOKEAN OROGENY IN MINNESOTA AND UPPER MICHIGAN:
A COMPARISON OF THE STRUCTURAL GEOLOGY OF THE MICHIGAMME
AND THOMSON FORMATIONS**

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An examination of mesoscopic structures and microstructures and a preliminary strain analysis in the Michigamme Formation along a transect from Covington to Iron Mountain, Michigan, reveal a striking similarity to the structural geology of the Thomson Formation in east-central Minnesota. In Minnesota there are two distinctly different structural terranes, as there are along this transect in Michigan.

In the northern terrane in Minnesota, the dominant structural features are a single set of open to close, upright, sub-horizontal, east-west trending folds, with a single, well-developed foliation that is axial planar to the folds. Where fold axial surfaces are not dipping vertically, the vergence is to the north, with axial surfaces dipping steeply south. Fold axes are sub-horizontal except where folds die out rapidly along strike, where axes may plunge up to 60°. The foliation is a continuous slaty cleavage in fine-grained units and a disjunctive spaced cleavage in the coarse-grained graywacke beds. At several places kink bands deform this foliation, indicating a small amount of late sub-vertical shortening. Deformed concretions, mud chips, and a thin conglomerate unit allow the determination of finite strain in the northern terrane. Strain ellipsoid shapes plot in the flattening field ($0 < k < 1$) with X:Y:Z ratios averaging approximately 7:4:1. Z is horizontal and oriented north-south. The east-west, vertical foliation approximates the XY plane of the strain ellipsoid.

In Michigan, in the area from Covington south to the Baraga County-Iron County line (a distance of about 15 km) structures similar to the northern terrane in Minnesota are found. A single foliation is found, again a continuous slaty cleavage in the fine-grained units and a disjunctive space cleavage in the coarse-grained graywacke beds. The attitude of the cleavage changes somewhat from north to south along the transect, and is axial planar to, and shows normal bedding-cleavage vergence relationships (between slate and greywacke beds) to some mesoscopic folds that exist. These folds are upright in the southern part of the transect, but axial surfaces dip as gently as 40 to 50° south at Covington, showing northward vergence. Where fold axes can be found, they are sub-horizontal, and bedding-cleavage intersections along the transect are sub-horizontal. Late-stage kink bands also exist here, and are also gently dipping. Deformed concretions and mud chips exist in these rocks, and a preliminary analysis reveals flattening strains similar to those in the northern terrane in Minnesota.

In the southern terrane in Minnesota, two main periods of folding have been identified. Early phase (F_1) folds are isoclinal and recumbent, with east-west trending fold axes. Minor F_1 folds as much as a meter or so in amplitude and wavelength have been observed, but nappe-scale structures of this phase have been interpreted based on several lines of reasoning including bedding-cleavage vergence relationships and facing directions of F_2 folds. An early foliation, axial planar to these folds, is found throughout the southern terrane. As the folds are isoclinal and hinge regions of folds are rare, this foliation is nearly always sub-parallel to bedding. A second phase of folding (F_2) is found in the southern terrane in Minnesota. These folds are of similar style, attitude, and geometry to the only folds found in the northern terrane. A spaced crenulation cleavage is widespread in the southern terrane, in an attitude which is axial planar to the F_2 folds. A strong lineation exists, parallel to the intersection of the two foliations. Strain analyses in the southern terrane in Minnesota from deformed conglomerate clasts and mud chips indicate that very large flattening strains accompanied the development of the early folds and foliation. In the Thomson Formation in Minnesota, metamorphic grade increases progressively from north to south.

The structural geology of rocks exposed in Michigan at Horse Race Rapids just south of Crystal Falls, and at Steele Farm and along the Sturgeon River just north of Iron Mountain, is quite similar to the structural geology of rocks in the southern terrane in Minnesota, and distinctly different from the rocks of the northern terrane in Michigan, in the area just south of Covington. In this southern terrane in Michigan two phases of folding are also found. The early phase is again isoclinal and recumbent, and there is a well-developed foliation axial planar to the folds. F_1 fold hinges are quite rare so this foliation is usually found to be sub-parallel to bedding. F_2 folds are open, upright, and sub-horizontal. A spaced crenulation cleavage is found in some places, in an attitude which is axial planar to the F_2 folds. A lineation is found that is parallel to the intersection of the two foliations, and the metamorphic grade of the rocks in the southern terrane is higher than in the northern terrane. No strain analysis has been done in the southern terrane in Michigan. The region of the boundary between the northern and southern terrane in Michigan is not as well exposed as is the boundary region between the northern and southern terranes in Minnesota. It is in this region in Minnesota that the best evidence for nappe-scale structure is found. Based on the similarities in structural geology in both northern and southern terranes in the rocks in Minnesota and Michigan, it is suggested that the early phase of deformation in the southern terrane in Michigan did involve a great deal of strain, and the development of large-scale features probably including fold and thrust nappes.

The Mining and Geologic History of the Silver Islet Mine, and a Conceptual
Ore Genesis Model for the Deposit.

By Robert J. Horton

Silver Islet is located 20 miles east of Thunder Bay, about 3/4 of a mile off the Sibley Peninsula in Lake Superior. A silver vein discovered on the island produced an estimated 3 million ounces of silver during a 16 year period from 1868 to 1884. The island, roughly 10 feet high and 80 feet in diameter, is located at the intersection of a steeply dipping gabbroic dike, hosted in flat lying sediments, and a fault zone that strikes perpendicular to the dike. The silver ore occurs only in the portion of the vein confined within the dike; the ore abruptly stops where the vein intersects the sediments. Following is a brief summary of the mining and geologic history and a ore genesis model for the Silver Islet deposit.

MINING HISTORY

In 1845, prospector Joseph Woods patented 6400 acres along the Sibley Peninsula which he sold to the Montreal Mining Company the following year. The "Woods Patent" lay idle for over 20 years. In 1868, in an attempt to increase mining activity in Ontario, the Crown levied a two cent per acre tax on mining lands. This inspired the Montreal Mining Company to evaluate their holdings, including the Woods Patent. On July 10, 1868, while conducting a shoreline survey, an exploration party lead by Thomas MacFarlane landed on what is now Silver Islet and discovered the silver bearing vein. Five days later, 1,336 pounds of ore was shipped to Montreal. The ore assayed at 2,087 ounces of silver per ton. The Montreal Mining Company worked Silver Islet until mid 1870, producing 27,124 pounds of ore assayed at \$25,043.06. In August of 1870 the company sold all its north shore holdings for \$225,000.

The major obstacle facing the newly formed Silver Islet Mining Company was flooding and storm damage. The entire mine was below lake level and increasingly larger pumps were required when new leaks were encountered as the workings expanded. The mine was also vulnerable to violent southerly storms which generated waves large enough to wash completely over the island. In an attempt to protect the mine from storm damage, a cofferdam was constructed around the shaft and a wooden breakwall around the island. In December, 1874, a violent southeasterly storm swept away 350 feet of the islands' protective breakwall, composed of 20,000 feet of timber, 7.5 tons of bolts, and 5,000 tons of rock; and destroyed some of the mines above ground structures. An expanded breakwall was rebuilt, to act as a buffer against the waves, that increased the size of the original island 30 fold. The mine operated continuously from 1870 to 1884 except for periods devoted to exploration drilling and repair of storm damage. A shipment of coal failed to arrive during the fall of 1883, causing the mine to flood on January 20, 1884, when the pumps stopped for lack of fuel. At this point the mine had reached a total depth of 1,230 feet, and produced an estimated 3,044,000 ounces of silver worth \$3,500,000.

GEOLOGIC SETTING

The geology of the region consists of an Archean basement unconformably overlain by Proterozoic sediments. The Archean basement is part of the Wawa-Shebandowan subprovince, composed of mafic and felsic volcanogenic rocks, minor sedimentary units, and felsic and mafic plutonic rocks; with a greenschist metamorphic grade. Unconformably overlying this intensely deformed greenstone belt are the relatively flat-lying Proterozoic sediments of the Gunflint and Rove Formations. The Gunflint Formation consists of an iron-rich assemblage of stratified sediments. The Rove Formation is an extensive sedimentary deposit composed of black pyritic shale, argillite, and graywacke. The Rove Formation, up to 1200 feet thick, is disconformably overlain by the Sibley Group redbed sedimentary sequence. These rocks have been intruded by diabase and gabbro dikes.

In the vicinity of Silver Islet, the Rove formation has a shallow southeasterly dip. The sediments are intruded by a steeply dipping, northeast trending dike swarm. A series of parallel faults, striking northwesterly, cut the dikes and sediments and show 300 feet of vertical displacement.

The Silver Islet dike strikes N. 50° E., dips 75 degrees to the southeast, and is 350 feet wide at the surface, thinning to 250 feet at a depth of 560 feet. The gabbro dike has a metamorphosed contact with the host sediments, has assimilated blocks of shale, and is impregnated with graphite and pyrite. The dike has a considerable length, extending at least 1600 feet to the northeast and 1200 feet southwest of the island. Along strike, the dike is thought to outcrop on other islands over a distance of 60 miles. The Silver Islet vein varies in width from a few inches to 50 feet, strikes N. 35° W. and dips 85 degrees to the southeast. The vein has a strike length of at least 1800 feet. In the sediments, the vein is composed of calcite, barite, fluorite, and quartz; however, within the confines of the dike the veins' composition is a fine grained, homogeneous pink dolomite with minor quartz. The vein is generally thicker in the dike than in the sediments.

The vein contains both primary and secondary ore, which always occur in the presence of graphite. About 90 percent of the ore is primary, and found throughout the mine in varying degrees of richness. The primary ore is composed of silver, argenite, niccolite, galena, sphalerite, marcasite, cobaltite, smaltite, domeykite, chalcopryite, and tetrahedrite in a pink dolomite gangue. These ore minerals occur as disseminated grains, intergrown aggregate clusters, and dendritic forms, and range in size from microscopic to 3 mm³. The secondary ore occurs in groups of pockets irregularly distributed throughout the vein system. Deposited as replacement bodies, cavity fillings, vugs, linings, and veins, these secondary ores occur at the surface to a depth of 560 feet. The secondary ore is always in close proximity to primary ore. Secondary ore minerals include quartz, calcite, barite, marcasite, erhrthrite, and annabergite. Native silver occurs as wires, leaves, and nuggets, commonly in clusters up to 3 cm³. During the operation of the mine, two massive secondary deposits of native silver were discovered. The first "Bonanza" contained 721,632 ounces of silver. A winze through the second bonanza showed native silver on four walls for a length of 60 feet. The following scenario is a conceptual model for the Silver Islet deposit.

ORE GENESIS MODEL

The Archean basement is a source of metamorphosed, metal-rich, volcanogenic rocks. During the Archean-Proterozoic unconformity (the Eparchean interval) the Archean rocks were exposed to an extremely long period of intense physical erosion and unique chemical and climatic environments, which produced a deeply weathered surface. This regional weathering profile contained a variety of elements, derived from metal-rich Archean rocks, that were sorted, fractionated, and concentrated by laterization and supergene processes. With the onset of Proterozoic sedimentation, the weathering profile was buried and preserved in a developing basin. The depth of burial increased as the basin evolved. If a sufficient geothermal gradient was established, deep circulating basinal brines may have further concentrate elements within the buried lateritic zone, or redistributed them to other horizons.

The intrusion of the gabbro dikes assisted in the ore genesis in several ways. The dikes contributed to a higher heat flow and provided a possible source for additional metals and fluids. The dikes also partitioned the sedimentary pile and the underlying basement rocks into restricted circulating cells. Most importantly, after solidification and subsequent faulting, the dike provided a conduit and host rock for ascending ore-bearing fluids. Hydrothermal fluids obtained metals from the lateritic horizon located within the restricted circulating cells adjacent to the Silver Islet dike. Heat was provided by the geothermal gradient, supplemented by the Keweenaw rifting and associated intrusive events. The fault, produced during later stages of the rifting event, provided a conduit. Primary ore was deposited over a relatively short period of time, in a graphite rich portion of the dike. The primary ore was precipitated by reductions in temperature, pressure, and reducing conditions confined within the dike. Secondary ore deposits formed over a relatively long period of time, possibly as epithermal or mesothermal systems leached silver out of the primary deposit and redeposited it as cavity fillings.

GEOPHYSICAL INVESTIGATIONS, INTERNATIONAL FALLS AND
ROSEAU QUADRANGLES, MINNESOTA-ONTARIO

By

Robert J. Horton, and Bruce D. Smith

Regional aeromagnetic and gravity data have been compiled for the International Falls and Roseau two degree quadrangles by the U.S. Geological Survey (USGS) in cooperation with the Minnesota Geological Survey (MGS) and the Geological Survey of Canada (CGS). This compilation was done as part of the Conterminous United States Mineral Assessment Program (CUSMAP) for the two quadrangles located along the U.S.-Canadian border. Bedrock in the area is largely buried by Quaternary glacial deposits. Therefore, maps of the bedrock geology are based primarily on interpretation of regional aeromagnetic and gravity data supplemented by mapping sparse outcrops and lithologic logging of a limited number of drill holes. Maps of gravity and magnetic anomalies are presented here along with various maps illustrating computer processed enhanced maps produced to aid geologic interpretation of the study area.

Data compilation for preparation of aeromagnetic maps includes existing data from MGS and CGS which supplements new data collected by the USGS. The new airborne survey was flown with a line spacing of 1/4 mile at an elevation of 300 feet with a high-precision proton sensor. A variety of navigation systems including radar transponder, LORAN, and photo-recovery were used in the USGS project in order to overcome problems in flight line location over largely featureless terrain. The new USGS data were processed along with the other aeromagnetic data to produce an IGRF-corrected total magnetic field map of quadrangles.

Complete Bouguer anomaly gravity maps were also prepared as part of the CUSMAP study using new data collected for the project combined with U.S. Department of Defense gravity data base. The new data were collected in cooperation with the Minnesota Department of Natural Resources-Division of Minerals and in cooperation with on-going gravity surveys being done by the MGS. Detailed profiles were made by the USGS to better define important geologic features interpreted from preliminary gravity anomaly maps. The total data set was then processed to produce terrain-corrected Bouguer anomaly maps of the two quadrangles.

The compiled aeromagnetic data was processed to compensate for inclination and declination of induced magnetic fields which offset boundaries of causative sources from magnetic highs. The reduction-to-the-pole program shifts the magnetic highs associated with dipolar magnetic lows to be more coincident with the source. Judicial use of this enhanced map with the original magnetic map facilitates geological interpretation of the geophysical data.

Gravity and magnetic data was further processed to produce color shaded relief (CSR), horizontal derivative, and edge enhanced maps. The CSR and horizontal derivative maps emphasize subtle linear features and level changes in anomaly intensity. For example, the CRS map of the reduced aeromagnetic data dramatically emphasizes linear anomalies due to northwest striking diabase dikes. Edge enhanced reduced magnetic and gravity maps emphasize possible boundaries between geologic units with contrasting densities and/or susceptibilities.

Interpretation of detailed profiles of ground gravity and magnetic surveys through computer modeling of possible bedrock contacts suggests size, shape, attitude, and physical properties of causative bodies. Geophysical interpretation of these maps can be integrated with interpretation of geological data to yield an effective mineral resource assessment of the study area.

For CUSMAP studies described here, regional and site specific electrical geophysical methods were used. Application of electrical geophysical methods is well known in the glacial covered terrain of the Canadian Shield and is routinely used by mineral exploration companies in Minnesota. Current implementation of these airborne and ground electrical methods are too costly to apply over a complete $1^{\circ} \times 2^{\circ}$ quadrangle. The purpose of this presentation is to demonstrate some cost-effective applications of new airborne and selected ground electrical methods in regional mineral resource assessment programs. Digital terrain data was processed to enhance trends to aid in interpretation of other geophysical and geologic data.

Interpretation of airborne EM anomalies and trends which might be due to conductive till is facilitated by comparison with trends shown in a colored shaded relief map of topography. This map is also useful in showing trends of both the exposed bedrock and glacial deposits. East-west trends in the central part of the International Falls Quadrangle result from glacial erosion and deposition of thick lacustrine sediments by the ancient Lake Agassiz.

Ground electrical surveys were made in selected parts of the study area to supplement interpretation of bedrock features and to estimate the thickness of glacial till. Frequency and time domain sounding methods were used to estimate till thickness. Measurements of signals from natural electrical fields (such as generated from thunderstorms) using Audio-magnetotellurics (AMT) and telluric profiling methods added further constraints on overburden thickness and bedrock conductors.

Hypabyssal rocks of the North Shore of Lake Superior: evidence for polybaric fractionation in the Midcontinent Rift

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The hypabyssal rocks of the North Shore of Lake Superior are found as diabase sills and dikes, and are present both singly and in groups all along the shore from Duluth to the Canadian Border. Other clusters of dikes are also present around Lake Superior (1). The most noteworthy swarms on the North Shore occur near the Border, and as a major map unit in the region of Beaver Bay (e.g. 2). These rocks generally have olivine tholeiitic compositions, although other, more evolved compositions exist. The majority of the hypabyssal rocks of the North Shore post-date the extensive magmatism responsible for the lavas, and thus provide the opportunity to study magmatic products produced late in the evolution of the Midcontinent Rift.

Even though these dikes and sills appear very similar to one another in major element chemistry (most are high-Al), a striking range of compositions is apparent in the trace elements. Among the rare-earth elements (REE), the light REE range from ~10 to ~100 times chondrites, and the heavy REE range from ~3 to ~20 times chondrites (Fig. 1). Positive europium anomalies are present in the most primitive rocks and are absent to slightly negative in the more evolved. Such abundance variations of an order of magnitude suggest that a significant amount of fractionation was involved in the formation of these rocks.

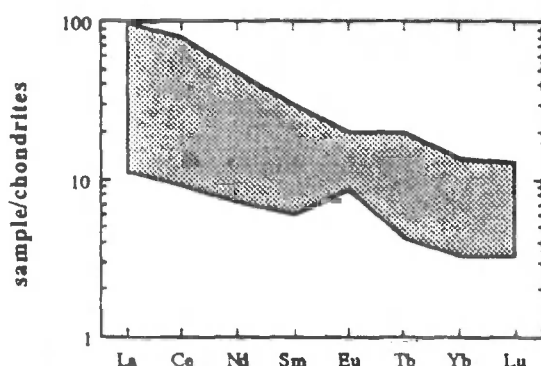


Figure 1. Diagram of chondrite-normalized REE data showing variation among the diabases of the North Shore of Lake Superior.

Analysis is ongoing, but there appear to be no major regional patterns in the chemical variations along the North Shore. Of the "evolved" material, the greatest amount is found near Duluth, but is present in places all along the shore. Since the hypabyssal rocks of the North Shore represent the final stage of the rifting process, the apparent random distribution of compositions along the shore is consistent with a well developed plumbing system allowing magmas to be tapped from common chambers and emplaced at widely spaced locations.

Fractionation at multiple levels in continental crustal regimes is becoming more and more recognized as an important process in the generation of magmas seen in continental settings

(e.g. 3-5). In these models, a magnesian melt is produced from the mantle, and is collected (underplated) at the base of the crust. Such a magma would crystallize olivine, then olivine and plagioclase, and eventually become saturated in clinopyroxene as well. Such an evolution would produce a high-Al magma as discussed by Klewin (5). If this same high-Al magma were then emplaced at a higher level in the crust, clinopyroxene would not be a stable phase due to the shrinkage of the pyroxene field with lowering pressure (e.g. 6,7), and only olivine and plagioclase would crystallize until the magma was once again saturated with respect to clinopyroxene. The suite of diabases from Lake Superior provides excellent evidence for just such a polybaric fractionation.

Since the primary difference between the two fractionation schemes is the presence or absence of clinopyroxene as a crystallizing phase, diagrams such as MgO vs CaO (Fig. 2) work quite well in displaying the difference since one quantity (in this case MgO) is not solely dependent on clinopyroxene crystallization, and the other (CaO) is dependent on clinopyroxene. For fractionation involving olivine and plagioclase, the concentration of MgO would be expected to drop due to incorporation in olivine, but CaO would remain relatively unchanged. When clinopyroxene begins crystallization CaO will drop, leading to a cross-trend on the diagram (Fig. 2b).

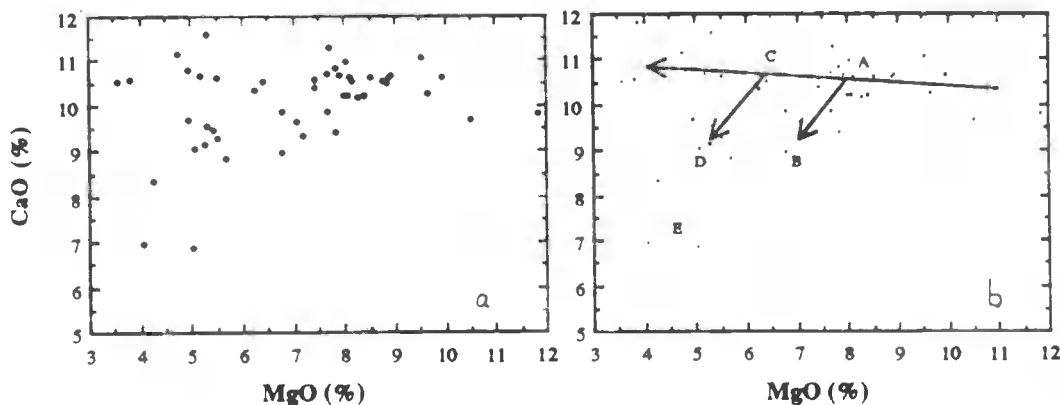


Figure 2. MgO vs CaO variation diagrams for the hypabyssal rocks of the North Shore from this study. Diagram "b" shows suggested fractionation paths.

In the diagrams of Fig. 2, most samples are on the roughly constant CaO path, indicating that olivine and plagioclase fractionation was a dominant mode. However, some cross-trends are present. These are consistent with a high-Al magma ("A") fractionating olivine, plagioclase, and clinopyroxene to produce "B" at some level in the crust. Continued evolution could produce the even more evolved material found in the chilled margins of the Lester River and Endion Sills of Duluth (point "E"). If the magma of composition "A" were emplaced at a higher level, the pyroxene stability field would be suppressed, and fractionation of olivine and

plagioclase would take it further down in MgO, to where clinopyroxene would be a crystallizing phase, i.e. at point "C". Crystallization would then lead to a progression of compositions toward that of "D". The presence of still other compositions out to very low MgO values with CaO ~10% is suggestive of fractionation at still higher levels in the crust. Three levels of fractionation has been suggested for the lavas of the North Shore Volcanic Group (NSVG) (5). In addition, there are several samples that contain very high amounts of MgO. While no genuine picrites have been described for the North Shore, these samples are more magnesian than the parents postulated for much of the rift magmatism. It is possible that these samples represent material brought up from the very base of the crust when the rift was the most developed, and represent material that was evolving toward the high-Al "parent" from some other, more primitive (picritic?) magma. These high-MgO rocks are somewhat similar to the high-MgO material found near the base of the extrusives on Mamainse Point, Ontario (8).

With regard to trace elements, it is not surprising to note that samples near points "B" & "D" showing evidence of the most fractionation on the variation diagrams, also have the highest REE abundances (50-100 times chondrites). Even the samples that represent crystallization in the absence of pyroxene show a general trend from lower REE abundance to higher as the composition goes from high MgO to lower (i.e. right to left in Fig. 2). Another point concerns the samples that may be called a "parent", namely at point "A". These are very similar in major element chemistry to the primitive olivine tholeiites of the NSVG (9), one of which was used as a parent in modelling presented by Klewin (5). However, the incompatible trace elements are enriched by a factor of two or more in the primitive diabases relative to the primitive olivine tholeiites of the NSVG. This may perhaps be due to replenishment of the fractionating subcrustal chambers, akin to the process described by O'Hara (10), and consistent with the younger hypabyssal rocks tapping a later magma than the NSVG lavas.

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STRATIGRAPHIC AND STRUCTURAL EVOLUTION OF THE NORTHERN ITASCA METAVOLCANIC BELT, NORTH-CENTRAL MINNESOTA

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Geologic mapping in northeastern Itasca County is providing new insight into the makeup of the Archean, largely supracrustal complex known as the northern Itasca metavolcanic belt (NIMB). The NIMB is the western equivalent of the Wawa Subprovince of the Superior Province. It is bounded on the east, west, and south by granitic rocks. To the north, splays of the Vermilion fault zone separate the NIMB from metasedimentary rocks of the Vermilion Granitic Complex (Quetico equivalent). Although exposure is generally less than 5 percent, cores from exploration and scientific drilling, together with new aeromagnetic data (Bracken and Godson, 1988), fill data gaps between outcrop areas. Detailed modeling of magnetic and E-M data by the U.S. Geological Survey is providing valuable information to aid geologic interpretation in the Effie-Coon Lake area (western third of map area) where exposure is minimal. A cooperative study with the Minnesota Natural Resources Research Institute is underway to define geochemical characteristics of the NIMB. A data base of several hundred analyses is on file.

Although the stratigraphy is complicated by folding and faulting, rock units are generally younger to the north within the mapped area. The supracrustal units (Fig. 1) in apparent stratigraphic order (oldest-youngest) and are as follows: Units 1, 2, and 3 occur on two limbs of a large fold surrounding the Wasson Lake pluton. The stratigraphic sequence differs somewhat between these two limbs. On the southeast limb, unit 1 is broadly and irregularly transitional upward from tholeiitic volcanic rocks to calc-alkalic volcanic and volcanoclastic rocks and discontinuous iron-formation. Mafic, tholeiitic volcanics interdigitate with iron-rich strata on the north limb. Unit 2 conformably overlies unit 1 and consists of a monotonous sequence of pillowed and massive metabasalt flows and hypabyssal sills. This sequence contains evidence of upward-shoaling deposition (Jirsa, 1988). Unit 3 contains dacitic to andesitic volcanic and derived clastic rocks. It is locally interbedded with units 1 and 2. Unit 4 is the base of a second major volcanic cycle and consists of high-iron tholeiitic metabasalt flows and sills that are locally magnetic. Unit 5 contains mafic and ultramafic sills, collectively known as the Deer Lake Complex, that intrude both a small area of compositionally similar flows and the predominantly dacitic volcanic and clastic rocks of unit 6. The contact between units 4 and 6 extends more than 50 km, but its nature is enigmatic. Unit 7 is a poorly exposed, south-topping, metabasalt sequence.

The inferred tectonic and plutonic history can be divided into four main elements listed chronologically below:

1. D_1 deformation involved predominantly north-south compression with local perturbations related to diapiric rise of plutons. One such area is adjacent to the Wasson Lake pluton which was emplaced into border rocks causing folding and migmatization prior to the second deformation.
2. D_2 is a northwest-oriented transpressional deformation. The same style of deformation 60 km to the east in the Vermilion District (Hudleston and others, 1988) implies that D_2 was a regional transpressional event, affecting a large area of the Archean crust.

3. Northeast-trending, dominantly sinistral faulting and syn- to post-tectonic emplacement of variably magnetic, syenitic to monzonitic intrusions (Bello Lake, Coon Lake and Linden plutons).

4. Ubiquitous, northwest-trending, mostly dextral faulting. Many of these faults appear to be splays or to be otherwise related to the Vermilion fault zone. The latest and most brittle of these faults are more north-northwest-trending and many are now occupied by Proterozoic diabasic dikes.

Some field and analytical support was provided by the Minnesota Department of Natural Resources. Scientific drilling was supported by the Minnesota Legislature under the Minerals Diversification Program. Geophysical data were provided in part by the CUSMAP program of the U.S. Geological Survey.

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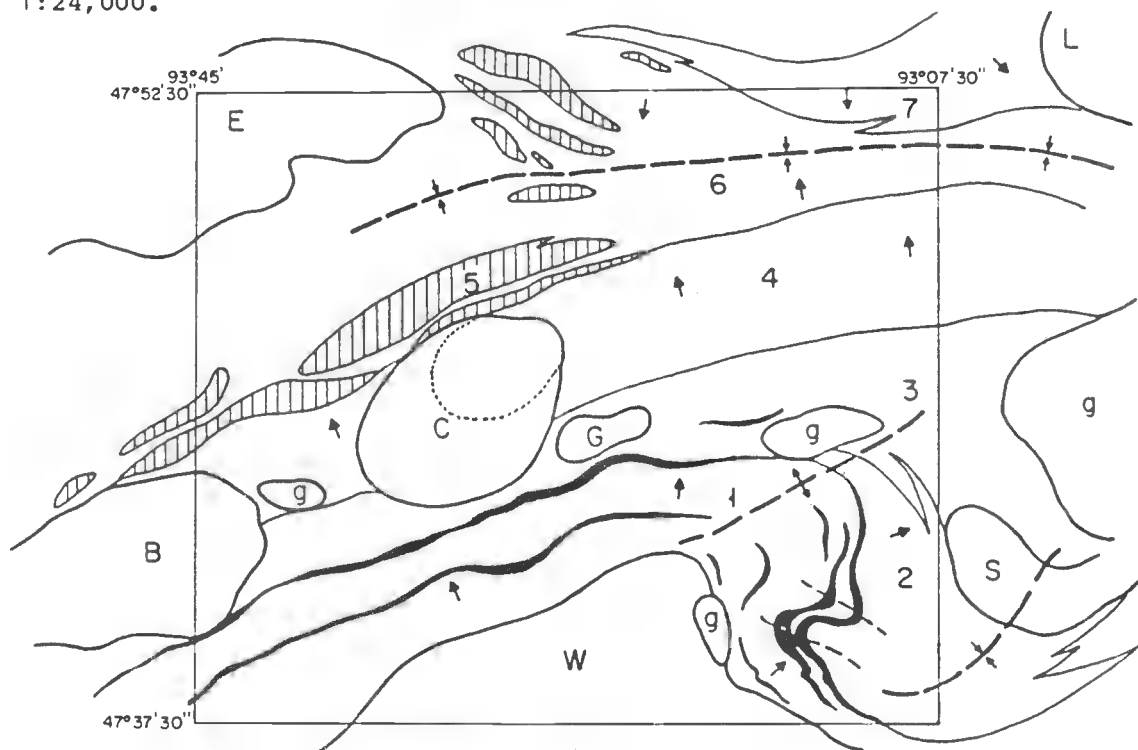


Figure 1. Schematic pre- or early faulting reconstruction of the northern Itasca metavolcanic belt. Supracrustal units 1-7 are described in text. Small arrows indicate direction of stratigraphic topping. Black units are iron-formation-bearing. Vertically ruled units are ultramafic and mafic sills of the Deer Lake Complex or associated with it. Tonalitic to granitic intrusions inferred to be early (pre-D₂) are the Wasson Lake pluton (W), Effie pluton (E), and G. Late, potassic or alkalic intrusions are the Bello Lake (B), Coon Lake (C), Linden (L), and Side Lake (S) plutons. Little is known of the other intrusions labelled g.

Jacobsville Sandstone and Tectonic Activity

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Between Keweenaw Bay and Ironwood the Jacobsville Sandstone (Jss) occupies a portion of a rift flank basin along the south side of the Midcontinent Rift System (MRS) and provides a record for late-tectonic activity along the MRS (Kalliokoski, 1989). The sandstone rests on the Powder Mills Group of lavas (PMG; about 20,000' thick). The lavas show a weathered surface at three localities. A thick lava plateau probably existed south and east (Hubbard, 1975), above the reversely polarized PMG dikes (Cannon, 1986). East of Lake Gogebic the PMG dips 10-15°N under the Jacobsville (Fritts, 1969), with 5,000' of original thickness remaining at the outcrop. West of Lake Gogebic these sequences dip 60-90°N and lie unconformable under the Jss (Hubbard, 1975). Here the PMG and its basement underwent a rotation to the north, accompanied and followed by erosion. A cryptic fault through Lake Gogebic (Klasner and Jones, 1979) may have accommodated this rotation and defined the east margin of a tectonic highland. About 15,000' of PMG had been eroded by Jacobsville time.

Only a few hundred feet of stratigraphic section can be constructed from the gently dipping Jss along Keweenaw Bay, but more complete sections are in available drill cores and logs (Fig. 1). TT-6 (2845') bottoms in coarse, quartz-rich conglomerate. The core is of pebbly and very coarse-grained sandstone, with 1% shale and 9% conglomerate (pebbles up to 4"). AE-1 (2298') bottoms in saprolite-covered basalt. The core lithologies are much finer grained than in TT-6. RL-1 (3620') bottoms in sandstone. In his M.S. thesis Bowers (1989) divides the core into four units with boundaries near 400, 1700 and 2500 feet. The uppermost unit resembles the classic red Jss but the others do not. These lower units show thin beds of white sandstone, red siltstone, and minor grit, with the three units differing in texture and relative lithologic abundances. RL-1 shows a fining upward sequence expressed by the upward increase in shale and siltstone (Fig. 1). Taken together, the three logs show a fining from west to east. The sections satisfy an alluvial fan model (Kalliokoski, 1982).

The westward coarsening suggests that the area southwest of Lake Gogebic became elevated in early Jacobsville time, and that tectonic forces maintained a northeast draining basin during the deposition of more than 3,000 feet of sediment. There is other evidence as well for possible tectonic activity during Jacobsville deposition:

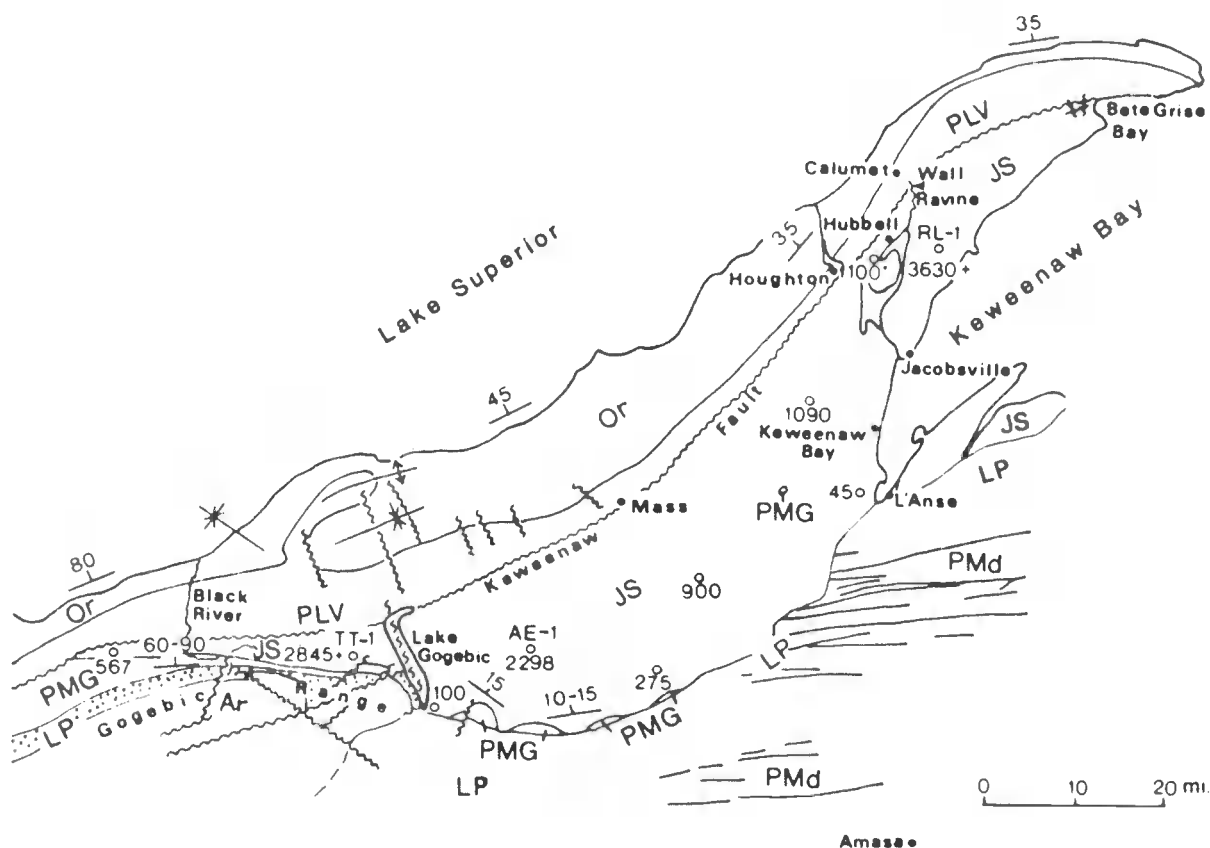
1. A flexural model for a subsiding MRS basin, such as that suggested by Peterman and Sims (1988) requires for the Jss, uplift and erosion to the south of a hinge and subsidence to the north. This would explain the preservation of paleosols under the Jss. The Goodman Bulge (Peterman and Sims, 1988) might have undergone coeval uplift.

2. In the Bete Grise Bay area some clasts in the Jss are remarkably similar to lithologies in the PLV, suggesting that there had been sufficient uplift along the Keweenaw reverse fault to remove the Oronto cover and expose the PLV (Brojanigo, 1984).

The position of the paleosol localities suggests that the hinge line between areas of deposition and erosion must have been many miles south of the current southern limit of the Jss. The flexure could have arisen from southerly thrusting along the Keweenaw fault or from the cooling of the MRS crust.

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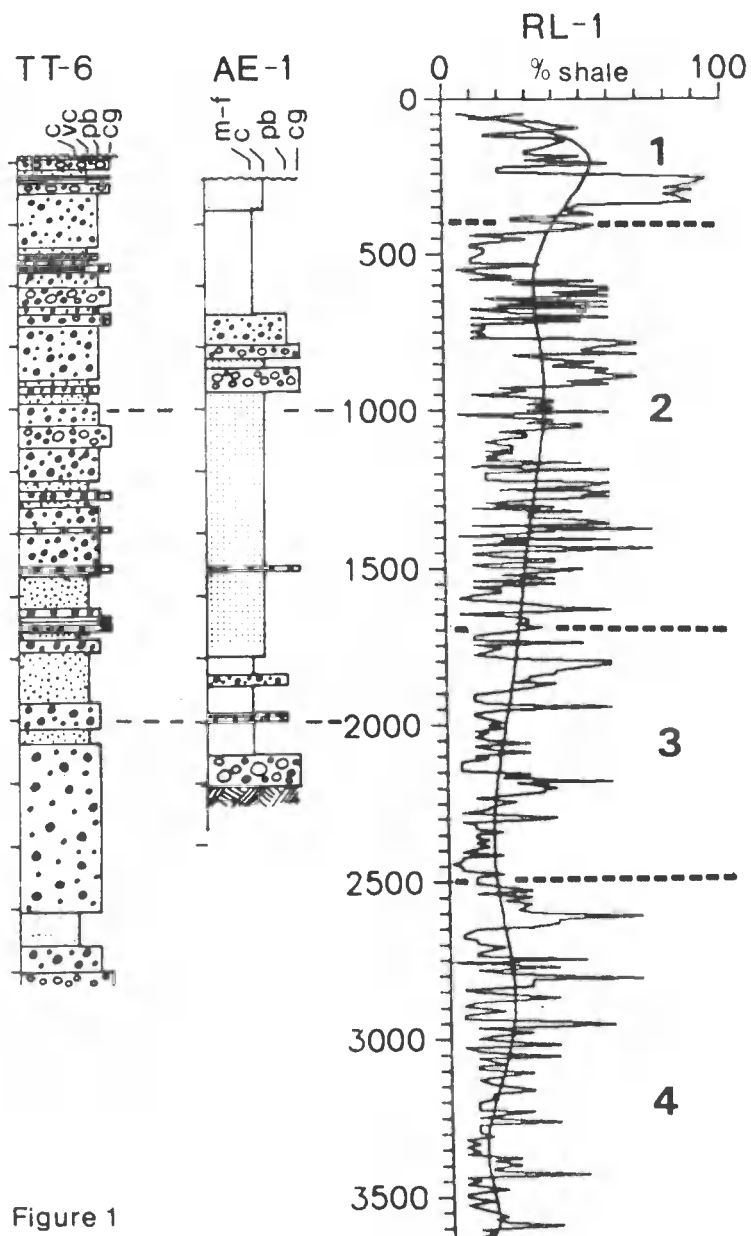


Figure 1

Logs of holes in the Jacobsville Sandstone.
 TT-6 (SW $\frac{1}{4}$ Sec. 33, T48N, R43W); AE-1 (W $\frac{1}{4}$ Cor.
 Sec. 36, T48N, R40W); RL-1 (Sec. 14, T55N,
 R32W).

Gravity survey of a portion of the Quetico and Wawa subprovinces near
Thunder Bay, Ontario.

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Ontario and S. P. Cheadle, Department of Geology, University of Calgary,
Calgary, Alberta.

In this study, 350 new gravity stations are combined with 50 previously surveyed stations in a detailed Bouguer anomaly map of a portion of the Quetico and Wawa subprovinces north and west of Thunder Bay, Ontario.

In general, high gravity values characterize the southern and southwestern part of the area where metavolcanic rocks of the Wawa subprovince dominate. Much of the Quetico subprovince forms a broad gravitational low reflecting extensive exposures of gneisses, schists, and migmatites. Conversely, well defined gravity lows are associated with several granitic intrusive bodies.

Models of subsurface configuration of the density contrasts representative of major rock units show a trough-like structure for the metavolcanic rocks of the Wawa subprovince. This trough-like structure is flanked by a domical feature in the granitoid rocks to the south.

North of the metavolcanic rocks, a succession of low-grade greywackes and slates occupy a basinal structure. This structure together with that of the metavolcanic rocks and granitoids form the subsurface configuration of the Wawa subprovince in this area.

The gneisses, schists, and migmatites of the Quetico subprovince form a thick southward dipping wedge-shaped structure which underlies the structures of the Wawa subprovince. This wedge-shaped structure is underlain by a model unit of greater density representative of mafic gneisses and amphibolites. The denser substratum is modeled with dislocations corresponding to the Quetico and Hawkeye Lake faults.

The cross sectional and three dimensional models suggest a combined process of vertical tectonism and lateral accretion for the crustal evolution of this part of the Superior Province.

Deformation of the Lyon Lake Massive Sulphide Deposit,
Wabigoon Subprovince, northwestern Ontario¹, Canada.

E.R. Koopman², B. Dubé³, J.M. Franklin², K.H. Poulsen², and
M.R. Patterson⁴.

The Lyon Lake deposit is a typical Zn-Cu-Pb-Ag volcanogenic massive sulphide deposit located in the Sturgeon Lake area of the Wabigoon volcano-sedimentary Subprovince of the Archean Superior Province of the Canadian Shield. The stratiform deposit is hosted by a quartz crystal rich fragmental rhyolite and its hanging wall is the basal mafic member of the overlying volcanic cycle. The footwall to the ore horizon consists of an upper rhyolitic unit composed of interbedded ash and lapilli tuff, immediately underlain by a lower rhyolitic unit of coarsely fragmental rock. Underlying the rhyolite, a fining upward sequence of sedimentary rocks comprised of greywacke, quartzose siltstone, graphitic shale, massive po-py bands, and capped by an extensive iron-carbonate and/or iron oxide Banded Iron Formation(BIF). The occurrence of a BIF underlying the massive sulphide horizon indicates that low temperature hydrothermal venting occurred prior to sulphide deposition. Massive sulphides form several stacked or en echelon lenses, and comprise discontinuous and contorted bands of coarse grained sphalerite and pyrite. All stratigraphic units, as well as dykes, and ore are folded(Fig. 1). The dominant structural feature controlling ore distribution is a major open fold characterized by a hinge line trending east-southeast(Fig. 1). Hinge lines of mesoscopic folds, foliation, and striations measured on bedding, foliation, and fault planes are all subparallel to the hinge line of the major fold and indicate a direction of stretching parallel to the fold axis. Observed faults have limited control on ore distribution, because there is no significant stratigraphic or ore displacement related to them. However, faulting is consistent with the style of folding. The contact between the hanging wall mafic unit and footwall rhyolite is characterized by a high strain zone, possibly a fault. Mineral lineations and striations on foliation planes are subparallel to the mesoscopic folds, and suggest that this high strain zone may be related to folding. A structural contour map of the hanging wall-footwall contact indicates that the dip of this contact is shallowing in an eastward direction reflecting the plunge effect of the major open fold. The deformation at Lyon Lake has resulted in the re-orientation of portions of orebodies into attitudes that are much shallower than the steep regional dip. Structural analysis has assisted in the increased effectiveness of developing and mining these flatter orebodies.

¹ Contribution to the Canada-Ontario Mineral Development Agreement 1985-1990.

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COMPOSITE SECTION 525' LEVEL - 1800' LEVEL
SECTION 12.200E

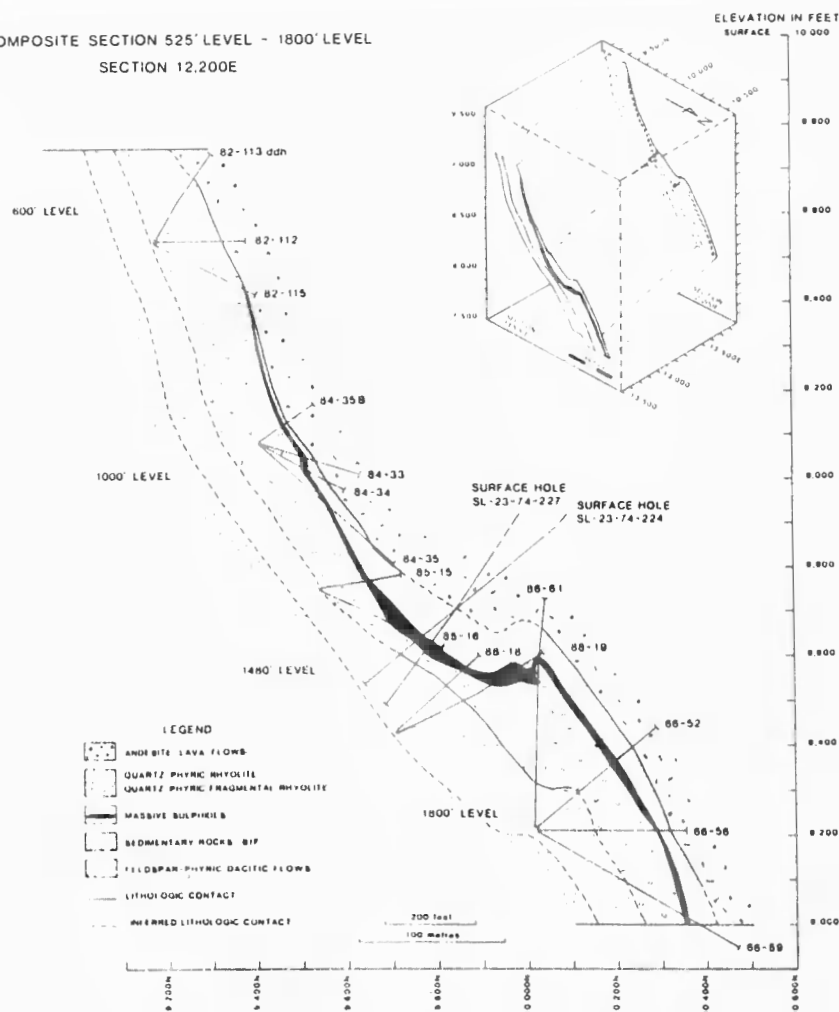


Figure 1. Composite cross section (12.200E) of the Sub Creek Zone. Inset: isometric projection of the deposit showing the plunge of the major flexure. North arrow indicates Mine North which is 40° east of true north (Note: Section 13.500E is a projection of Section 12.200E).

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POTENTIAL-FIELD ANOMALY MAPS OF THE LAKE SUPERIOR REGION

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New color magnetic and gravity anomaly maps compiled for GLIMPCE contribute to the understanding of the tectonic development of the Lake Superior region. Although the magnetic data were obtained from aeromagnetic surveys of variable specifications, a consistent data set was prepared by adjustment relative to a common reference field and by analytical continuation of all data to a datum 305 m above surface.

The availability of the digital data sets allows application of a variety of filtering techniques. Analysis by filtering involves conversion of the data into a form that enhances particular anomaly characteristics, such as wavelength or trend. Resulting filtered maps include (1) first vertical derivative to sharpen anomalies of shallow origin and small areal extent, (2) horizontal gradient to delimit lithologic or structural boundaries, and (3) color shaded relief to enhance particular anomaly trends. The filtered anomaly maps permit a refined interpretation of the geology of the Lake Superior region.

Basalt geochemistry as an indication of tectonic environment for the central part of the Hemlo-Heron Bay Greenstone Belt, Ontario.

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The Hemlo-Heron Bay greenstone belt is part of the east-trending, Schreiber-White River section of the Wawa Subprovince within the Superior Province of Ontario (Muir, 1986). The Hemlo area is located in the central part of the belt (Lat. 48°41.6'N, Long. 85°57.3'W). Hemlo U-Pb dates yield a 2,772 ma age for metavolcanics and 2,718 to 2,684 ma ages for granitoids intruding the supracrustal rocks (Corfu and Muir, 1986).

Lithologic sequences in the Hemlo area consist of thin flows and tuffs to thick piles of pillowed and massive basaltic metavolcanics, and to a lesser degree intermediate to rhyolitic metavolcanics (Kuhns, 1988). These metavolcanics are interlayered with thick sequences of meta-argillite and metagreywacke which represent turbiditic accumulations.

An Al versus Fe' ($Fe' = Fe_{Total}/Fe_{Total}+MgO$) variation diagram for Archean mafic rocks (Naldrett and Goodwin, 1977) applied to the Hemlo area mafic rocks indicate a dominance of basalt, and lesser magnesium- and ferrobasalt compositions (Fig. 1A). Major element data (not shown) indicate these basaltic rocks are of tholeiitic affinity.

Numerous trace element variation diagrams illustrating petrogenetic trends and tectonic environments have been constructed from modern and Phanerozoic basaltic suites (i.e. Pearce and Cann, 1973; BVSP, 1981). The application of these diagrams to Archean rocks is arguable, but their purpose is two-fold: (1) the identification of petrogenetic sequences, and (2) the identification of possible tectonic environments.

The Hemlo metabasalts bridge the MORB and IAT fields on Ti versus Cr and Ti/Cr versus Ni diagrams (Figs. 1B, C). The data also exhibit a gross trend from high Ni and low Ti/Cr (high Cr) to high Ti and low Ni and Cr concentrations, indicative of fractionation trends from magnesian-basalts --> basalts --> ferro-basalts. This apparent fractionation trend agrees with the distribution of data on Figure 1A. Volcanic cycles have not been resolved due to folding complications. A plot of Nb versus Zr shows a positive correlation also suggesting a fractionation trend in the basalts (Fig. 1D). The data plot within the "Type I" basalt field of modern MORB's (BVSP, 1981). Type I basalts erupt along topographically normal segments of mid-ocean ridge complexes, although similar signatures can also be obtained from island arc tholeiitic basalts.

Rare earth element patterns for the metabasalts (Fig. 2) indicate at least two principal groups of basalts (Fe-types *and* Mg-rich to normal-types), which support the trace element data above. Ferrobasalts yield

flat REE patterns and are typified by low $\text{Sm}_\text{N}/\text{Yb}_\text{N}$ and $\text{Ce}_\text{N}/\text{Sm}_\text{N}$ ratios, and high Sm_N and Yb_N concentrations (Figs. 1E, F). These characteristics are similar to ferrobasalts from the Blake River group, Ontario (BVSP, 1981). Flat REE patterns and total REE abundances of the ferrobasalts are compatible with some island arc basalts, and Phanerozoic Type I ocean floor basalts. Since Type II basalts are not present (Fig. 1D) island arc affinities are favored for the Hemlo area basalts. The second basalt group exhibits LREE enrichment, and has higher $\text{Sm}_\text{N}/\text{Yb}_\text{N}$ and $\text{Ce}_\text{N}/\text{Sm}_\text{N}$ ratios and Sm_N concentrations, and lower Yb_N concentrations than the ferrobasalts (Fig. 1E, F). The second group also yields slightly higher Mg concentrations, but the REE patterns are typical of Al-basalts in other Archean sequences (e.g. Blake River Group). The LREE enrichment is similar to some IAT's.

In summary, there are two principal groups of basalts in the Hemlo area. The first group is comprised of ferro-basalts, which exhibit flat REE patterns, low Sm/Yb and Ce/Sm ratios, and are similar to Phanerozoic island arc tholeiitic basalts. These rocks are not LREE depleted, therefore they do not specifically match Type I mid-ocean ridge basalts. The second group is less well defined, but is comprised of Mg-rich to normal basalts, which are LREE enriched, have high Sm/Yb and Ce/Sm ratios, and are similar to Al-basalts in other Archean terranes and may have IAT affinities. Some type of island arc setting is therefore favored for at least the central portion of the Hemlo-Heron Bay greenstone belt. This conclusion is in part supported by the presence of intermediate to felsic pyroclastics and turbidite basins, although more regional studies need to be completed.

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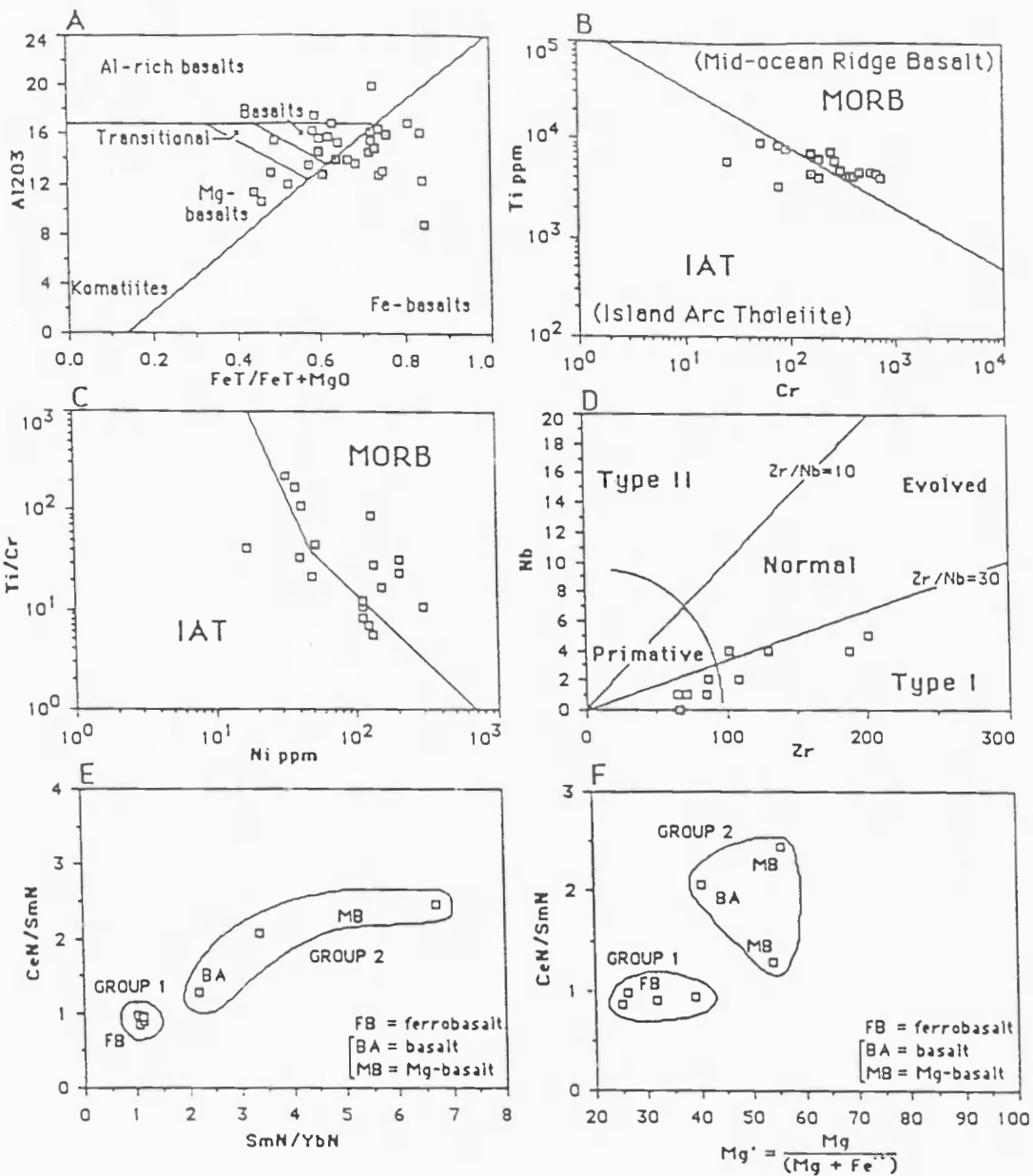


Figure 1. Major, trace, and rare earth element variation diagrams for Hemlo area metabasalts (see text for discussion).

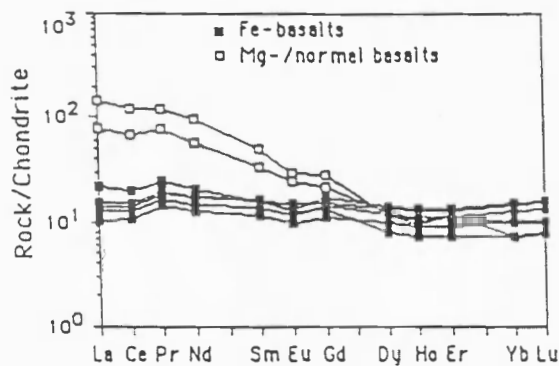


Figure 2. Rare earth element patterns for Hemlo area metabasalts (see text for discussion).

TECTONIC IMPLICATIONS OF THE STRUCTURE AND STRATIGRAPHY OF QUARTZITES IN CENTRAL AND SOUTHERN WISCONSIN.

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Structural and stratigraphic relationships of quartzite in central and southern Wisconsin provide constraints on the nature of the 1,850 Ma Penokean orogen and the 1,790 Ma Central plains Orogen. The Eau Pleine fault zone in central Wisconsin represents the boundary between rocks of the Wisconsin magmatic terrane on the north and a complex of Archean and Proterozoic rocks to the south, and appears to be a suture zone (LaBerge, Schulz and Myers, 1984, LaBerge, 1986). Isolated exposures of Early Proterozoic quartzite occur near, and south of the Eau Pleine fault zone and farther south in the Baraboo and Waterloo areas. Dott (1983) suggested that the quartzite and associated slate, dolomite and iron formation in the Baraboo Syncline represents a sequence of sedimentary rocks that developed on a passive continental margin. We concur and suggest that the sedimentary rocks formed on the passive margin of an Archean craton, remnants of which are exposed in central Wisconsin. LaBerge and Klasner (1986, 1988, in prep) have interpreted structural and stratigraphic relationships of these quartzites to suggest a major south-verging fold/thrust system that pre-dates the 1,760 Ma igneous event in southern Wisconsin, and appears, instead, to be related to a collisional event during the 1,850 Ma Penokean Orogeny.

This interpretation suggests that an Archean continental block with associated Early Proterozoic platform sediments on its margin, was accreted as an exotic terrane against the southern margin of the Wisconsin magmatic terrane. The platform sedimentary sequence was thrust southward onto the accreted Archean block, suggesting that Archean basement extended southward from the Eau Pleine fault zone at least to the Baraboo area.

Nd/Sm isotopic evidence from the 1,450 Ma pluton near the Wisconsin-Illinois border indicates that Archean crust did not contribute to that magma (Nelson and DePaolo, 1985). This suggests that Archean crust was not present in that area. Therefore, Archean crust evidently does not extend as far south as the Illinois border. The northern margin of the Central Plains orogen is projected through southern Wisconsin (Sims, Peterman, 1986), however, the nature of the boundary between the Central Plains orogen and the Penokean orogen is unclear. If the boundary was the result of northward subduction (Dott, 1983), an Andean margin on the Penokean would have developed. Southward subduction near a continental margin should produce major north-verging structures. Neither is evident in southern Wisconsin. North-verging structures are localized, brittle (shallow) features. The nature of Penokean-Central Plains juncture in this area is speculative. However, the lack of evidence for an Andean margin or northward vergence may suggest that rocks of the Central Plains orogen were emplaced by strike-slip movement in this region.

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Possible Late-Stage Thrust Faulting in a Keweenawan-Age
Accommodation Zone Beneath Lake Superior

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A research team coordinated by Argonne National Laboratory (ANL), under a grant from the Department of Energy's Office of Basic Energy Sciences (DOE/OBES), has entered into an agreement with Grant Norpac, Inc. (GNI) to license deep seismic reflection, gravity, and magnetic data in the Great Lakes. Data were licensed to assist DOE/OBES in the evaluation of the hydrocarbon potential of basins of Proterozoic age in North America. The initial acquisition includes 1,042 line kilometers of eight second data in Lake Superior. Data were collected using a tuned array of airguns and 120 groups of receivers spaced at 25 meter intervals along a 3.0 km streamer. The 60 fold data have been processed and migrated by GNI. Gravity and magnetic data were also recorded along most of the profiles.

Profiles are oriented parallel and perpendicular to strike of the Midcontinent Rift, tying together profiles collected by the GLIMPCE consortium in 1986. A 342.8 km profile (LS-08) from Duluth to 22 km east of Isle Royale parallels the axis of the rift. An accommodation zone in the center of the profile, associated with a gravity low, separates axially adjacent basins, and is composed of a massive block of Archean Gneiss. Modest thrusting and ramping up to the west is suggested on the east flank of the block. Thrusting must have occurred after volcanism but before deposition of the Bayfield and Oronto Sandstones which unconformably cover the truncated crest of the block and the eroded subcrops of volcanic flows. If thrusting has occurred in this environment, the proximity of the Grenville convergence in space and time might be a cause. If post-rift thrust or reverse faulting occurred parallel to strike, as well as across the strike of the rift as already reported, with thrusts generated by stress fields emanating from a converging plate margin, then the rift may have become a secondary tectonic feature, quenched by the prevailing tectonics of the Grenville. The unusually great vertical extent of the rift basin and its billion-year preservation is probably a consequence of its lateral immobilization at a rather early stage of its development.

*Work supported by the U.S. Department of Energy, Office of Energy Research, under Contract W-31-109-Eng-38.

CHARACTERIZATION OF GRAPHITE OCCURRENCES IN THE SOUTHERN AND WESTERN
PENOEKIAN OROGEN

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Electromagnetic (E-M) surveys, geologic mapping and bedrock drilling have shown that the rocks of the southern and western Penokean orogen contain an abundance of highly graphitic metasedimentary units (McSwiggen, 1987; Southwick and others, 1988). Many of these units have been drilled because of the very pronounced E-M anomalies associated with them, but very little detailed work has been done on the rocks, particularly with regard to the graphite. The purpose of this investigation is to characterize the concentrations and abundance of the graphite, nature and concentrations of secondary minerals, the origin of the graphite, and the formation of the graphite-bearing units.

The amounts of graphite and its crystallinity, the amount of precious and base metals, and the sediment source of the host rocks are all exceedingly variable. The graphitic units range from less than 1 percent carbon to more than 40 percent. The crystallinity of the graphite reflects the metamorphic grade of the locality. North of the Emily district the carbon occurs as amorphous material lacking any crystallization structure. In contrast, samples from the Moose Lake-Glen Township structural panel of Southwick and others (1988) contain moderately to highly crystalline graphite.

The host rocks of the graphite range in composition from slate to chert. The richest carbon samples contain the least amount of clastic sediments; this suggests that chemical sedimentation was the primary non-organic source of sediment in these samples.

The carbon-rich samples also typically contain anomalous values of base metals (Cu as much as 2900 ppm) and precious metals (Au as much as 350 ppb and Ag as much as 6 ppm). Preliminary results show that only half the gold in the sample is separated with the sulfide fraction. This suggests that half the gold may be adsorbed to the graphite. This relationship seems to hold regardless of the total gold or sulfur content of the rock.

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Funding Source: Minnesota Geological Survey and Mineral
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Glacial ice from two major accumulation centers advanced repeatedly across northern Minnesota throughout the Pleistocene. The Labradorean center contributed ice from the northeast, and the Keewatin center ice from the northwest. In general the geologic record of these ice movements is more complete, and therefore the drift stratigraphy more complex, south and west of the major bedrock outcrop area of northeastern Minnesota.

The mostly thin mantle of glacial sediment across northern St. Louis, Lake, and Cook Counties was laid down by the last (late Wisconsinan) ice advance of the Labradorean Rainy lobe. It consists primarily of locally derived, disintegrated Archean, and to the east Proterozoic, bedrock. The North Shore outcrop area of the three counties, however, was overridden by Labradorean ice moving out of the Superior basin, the Superior lobe, which laid down distinctive reddish sediment derived from disintegrated Keweenaw bedrock.

Late Wisconsinan Rainy lobe drift also overlies bedrock across northeastern Itasca County, northern and eastern Lake of the Woods County, and all but the southwestern part of Koochiching County (Martin and others, 1988; Martin and others, in progress), but is buried there by drift of the Keewatin Koochiching lobe. Sediment deposited by the Koochiching lobe, which is the surficial drift of northern Minnesota west of St. Louis County, is characteristically finer in texture than that of the Rainy lobe, being derived chiefly from Cretaceous shale and Paleozoic carbonate far to the west and northwest. Koochiching lobe drift, therefore, is a poor sampling medium for geochemical exploration.

The remainder of the bedrock surface of northern Minnesota is overlain by a complex pile of interbedded glacial sediment of both Labradorean and Keewatin provenance. Consequently, only the lower drift of both sources includes significant amounts of detritus from local bedrock. The position of locally derived clasts and the distance of transport are determined primarily by local bedrock topography and basal ice velocity. In general, subglacial transport carries entrained debris toward topographic lows, and transport distances through lows are longer than across intervening highs (Clark, 1987). Evidently the Koochiching lobe had a relatively high sliding velocity and transported basal debris long distances, whereas the Rainy lobe had a relatively low sliding velocity and transported newly entrained debris only short distances.

Ice-flow directions can be determined in bedrock outcrop areas from glacial striation measurements. Elsewhere drumlins and end moraines are good ice-flow indicators. In areas where basal drift predates geomorphic features, clast lithologic provenance implies general ice flow direction.

Partial support for this study was provided by the Department of Natural Resources Mineral Division through the Mineral Diversification Fund, and by the Minnesota Future Resources Commission.

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GEOLOGY OF THE BEAVER BAY COMPLEX, NORTHEASTERN MINNESOTA

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The Beaver Bay Complex (Grout and Schwartz, 1939; Gehman, 1957) is a supersuite of hypabyssal to plutonic gabbroic to granitic intrusions which were emplaced in the upper portion of the Keweenaw North Shore Volcanic Group (NSVG; Green, 1972) during the development of the Midcontinent rift system. The complex is best exposed along the Lake Superior coast near the towns of Beaver Bay, Silver Bay and Finland, Minnesota. From the lakeshore, the Beaver Bay Complex extends approximately 30 km to the north-northeast where it becomes covered by thick glacial till. Although it is stratigraphically and petrologically distinct from most rocks that comprise the deeper intrusions of the Duluth Complex, aeromagnetic and gravity anomalies over the covered area indicate a high ratio of intrusions to volcanic host rocks and thereby suggests that the Beaver Bay Complex is gradational into the Duluth Complex.

Geologic mapping at a 1:24,000 scale encompassing about 7.5° quadrangles (Silver Bay w/ Split Rock Point NE, Ilgen City, Finland and Doyle Lake) was initiated 4 years ago by the Minnesota Geological Survey in conjunction with the U.S. Geological Survey's COGEO MAP program. We report here on the major result of this ongoing project, which has elucidated much of the volcanic, intrusive and structural history of this part of the Keweenaw section.

The volcanic rocks that host the Beaver Bay Complex are dominantly flows of tholeiitic basalt to basaltic andesite, but also include arkosic interflow units and several thick (≤ 100 m) rhyolite flows (Miller and others, in press; Miller, 1988; Green, 1972). The typical shallow lakeward dip of most NSVG units is disrupted in this area due to block faulting during and after intrusion of the Beaver Bay Complex. Steep fault (and dike) trends are dominantly NE to NNE, parallel to the axis of the rift, and less commonly WNW. All NE-trending faults developed coeval with intrusion of diabase (now dikes) display downdrop of the lakeside block consistent with the rift basin deepening to the SE.

Current mapping indicates that the Beaver Bay Complex was emplaced in five major events. Each event produced a unique suite of rock types that reflect different parent magmas and modes of emplacement. In order of decreasing age, these intrusive suites are the Lax Lake gabbro, the Finland granite, the Sonju Lake layered intrusion, the Beaver River diabase, and the Silver Bay intrusions. The Beaver Bay Complex also includes several minor diabase intrusions whose genetic relationship with the major suites is unclear.

Subophitic olivine gabbro, oxide-rich gabbro, granophyric gabbro, and mafic granodiorite of the Lax Lake gabbro (Fig. 1) are the oldest intrusive rocks in the area. The shape of the intrusion is difficult to discern because the rocks lack internal structure and have been cut by younger intrusions (Beaver River diabase and Finland granite) and faults. The granophyric character and extensive hydrothermal alteration of most Lax Lake gabbro rocks probably is the result of their early emplacement into water-rich volcanics.

In sharp intrusive contact with the north margin of the Lax Lake gabbro suite is the Finland granite (Fig. 1), a homogeneous mass of pink to orange, granophyric, leucocratic, pyroxene granite. Although the granite contains abundant miarolitic cavities indicative of a vapor phase, the predominance of Fe-rich pyroxene over hornblende suggests that the parent magma was water-poor.

Bordering the Finland granite on the north and (as implied by aeromagnetism) west is a differentiated layered sequence of mafic cumulates termed the Sonju Lake intrusion (Fig. 1; Stevenson, 1974). This intrusion is the most completely differentiated body known in the Keweenaw section (Weiblen, 1982). It grades from a basal picrite/dunite to an upper apatitic ferrodiorite. In the northern part of the area, the roughly 1000-m-thick sequence dips gently ($15-25^\circ$) to the south. The laminated upper ferrodiorite is overlain by a massive granophyric quartz monzodiorite to granodiorite with prismatic pyroxene and olivine. This monzo/granodiorite grades into the Finland granite suggesting that it represents melting and partial assimilation of the granite which formed the roof of the intrusion. The east end of the Sonju Lake intrusion is abruptly truncated by a high-angle fault which juxtaposes the layered sequence and Beaver River diabase. Field relationships between Sonju Lake rocks and Beaver River diabase are unclear and allow the possibility that the units are coeval or that the diabase is younger.

Dikes and sills of ophitic olivine diabase, termed Beaver River diabase, are the most pervasive intrusions in the Beaver Bay Complex (Fig. 1). Steep dikes feed thick (≤ 100 m) subhorizontal sheets which form prominent flat-topped hills. The diabase intrusions are unique in that they contain abundant inclusions of anorthosite and less abundant granite, some as much as 100 m across, which tend to be concentrated in the lower parts of sheets. Typically, the anorthosites are massive, coarse-grained, and consist almost entirely of tabular calcic plagioclase (An 54-80; Morrison and others, 1983) with minor olivine, hypersthene, augite, and Fe-oxide. Some inclusions are tectonized and a few display modal

layering. The granite inclusions, being medium-grained and micrographic and containing Fe-pyroxene and miarolitic cavities, are probably xenoliths of Finland granite.

The **Silver Bay intrusions**, the youngest intrusive unit in the area, occur as many concentrically zoned bodies and as irregularly shaped masses within or adjacent to Beaver River diabase (Fig. 1). This spatial relationship suggests that the Silver Bay magmas were emplaced through the same conduits as the Beaver River diabase. Moreover, the abundance of Beaver River diabase inclusions, which are especially common in the intrusion centered south of Silver Bay, and the lack of any chill at the margins of the Silver Bay intrusions indicate that the ferrodioritic magmas were intruded soon after the diabase had crystallized. Zoned Silver Bay intrusions grade abruptly from a margin of coarse-grained, vari-textured granophyric olivine ferrodiorite to an interior of medium-grained, laminated, locally layered olivine ferrogabbro/diorite. Several irregularly shaped intrusions are composed of medium- to coarse-grained, granophyric olivine diorite, similar to ferrodiorite in the margins of the zoned intrusions. These bodies may represent deeper parts of intrusions which fed into zoned masses above. Some intrusions also contain significant amounts of mafic granodiorite to quartz monzodiorite which have resulted from local melting of felsic volcanics and deeper Finland granite, or perhaps from liquid immiscibility of the ferrogabbro magmas.

Petrogenetic models of the relationships between the various intrusive bodies which compose the Beaver Bay Complex and between these rocks and the underlying Duluth Complex must await more detailed investigations of their geochemistry. Field relationships and a minor amount of geochemical data, however, permit some preliminary conclusions. The parental magma to the Lax Lake gabbro was probably moderately evolved basalt which was driven to more felsic compositions by assimilation of nearby water-bearing volcanics. The wholly granitic composition and extensive volume of the Finland granite strongly suggests a crustal anatectic origin. Further geochemical studies should test whether this shallow intrusion could have fed any of the rhyolite flows in the area. Although the lithologies and modes of occurrence of the Sonju Lake, Beaver River, and Silver Bay intrusions are distinct, it is possible that these rocks are comagmatic. Preliminary geochemical data and the close spatial and temporal association of Beaver River diabase and ferrodioritic rocks of the younger Silver Bay intrusions suggest that the parent magmas of the latter may have been derived from further fractionation of Beaver River magma in deeper chambers. The Sonju Lake intrusion may have been one such chamber. Though the field relationships are obscure, the occurrence of anorthosite-bearing diabasic troctolite in the basal zone of the Sonju Lake intrusion suggests the possibility that the Sonju Lake body resulted from intrusion of Beaver River magma into a chamber of sufficiently large size that crystal fractionation could occur. It also follows that the Silver Bay magmas could have been tapped from the upper ferrodioritic differentiate of the Sonju Lake body. More geochemical data are currently being acquired to evaluate this model.

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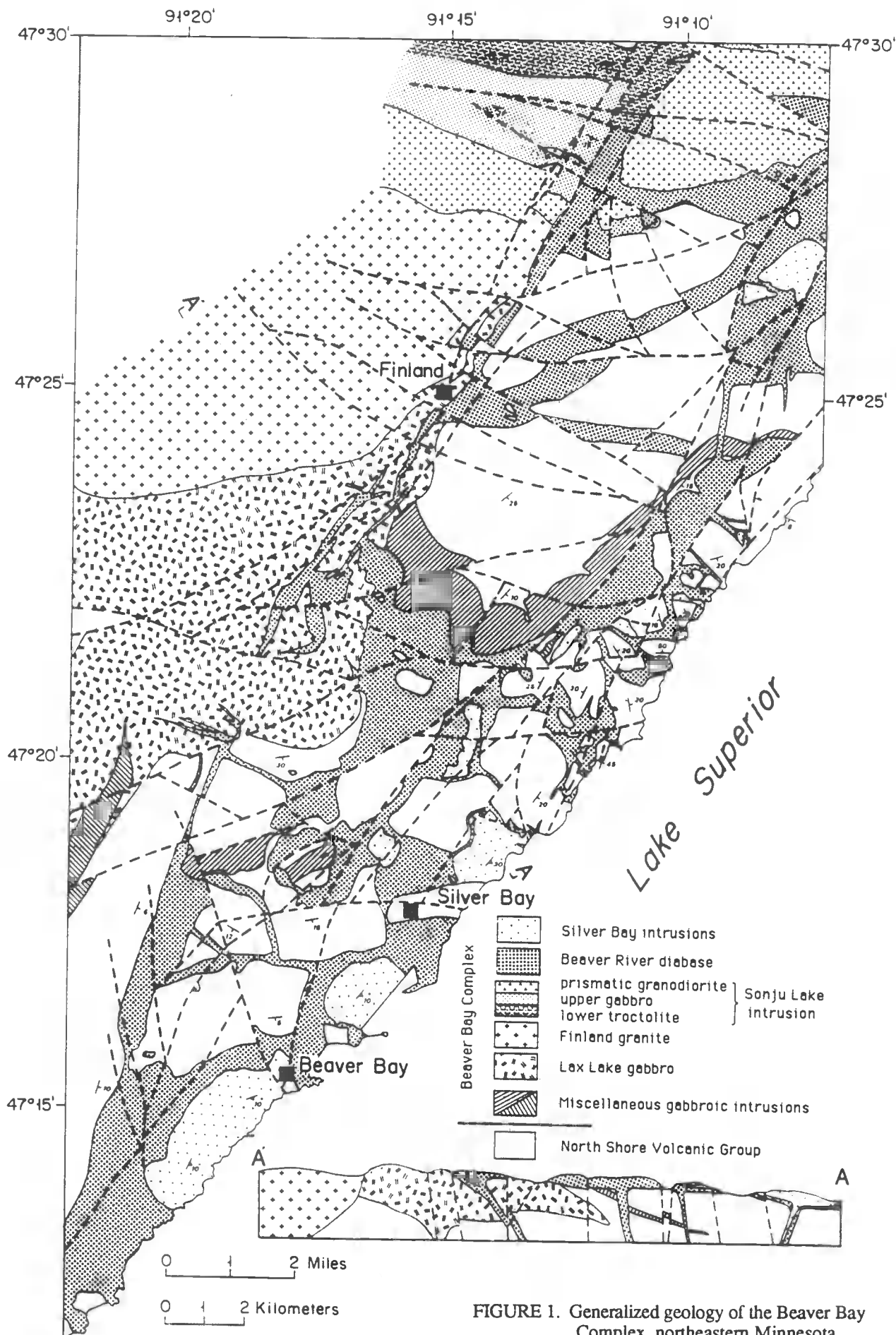


FIGURE 1. Generalized geology of the Beaver Bay Complex, northeastern Minnesota.

THE PALEOMAGNETIC RECORD OF LATE GLACIAL AND POST GLACIAL SEDIMENTS OF LAKE SUPERIOR

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The Late Quaternary sedimentary sequence consists of glacial till which was deposited about 9900 years ago during the last glacial advance into the Lake Superior Basin. In the Canadian portion of Lake Superior the till deposits are unconformably overlain by a thin sequence of bedded sands and silts which are conformably overlain by a thick sequence of varved sediments which in turn are overlain by postglacial silty clays. Paleodeclination and paleoinclination logs can be used to correlate and indirectly date cores of this sedimentary sequence that have been taken from the major basins of the Canadian portion of Lake Superior. In addition the paleomagnetic data obtained from six cores has been stacked to form 'type' paleodeclination and paleoinclination logs for Lake Superior. These 'type' logs can be correlated with the 'type' logs obtained for both Lakes Huron and Erie.

It is concluded that rhythmic sedimentation ceased prior to 9200 years BP in the southeastern lake proper and at about 8700 years BP in the southeastern bay areas. However rhythmic sedimentation continued until about 8200 years BP in the northern part of Lake Superior and until about 8000 years BP in the Nipigon Bay area.

FUNDAMENTAL UNIT DIFFERENTIATION OF THE MIDDLE PROTEROZOIC MIDCONTINENT RIFT SYSTEM, NORTH AMERICA

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ABSTRACT

Analysis of geophysical data within the Lake Superior basin of the Middle Proterozoic Midcontinent Rift system in central North America suggests a series of opposed, sub-regional half-grabens, displaying igneous and sedimentary infill packages separated by accommodation structures. We interpret five first-order rift segments (zones) identified by major interruption of gravity and magnetic patterns, seismic expression, and terrane composition separated by four first-order accommodation structures. Clockwise from the southwestern end of the rift, these segments are named the Kansas, Iowa, Superior, Mackinaw, and Maumee zones (fig. 1). Second-order rift segments (fundamental rift units) are separated by second-order accommodation structures. Within the Superior zone four such segments are now recognized and named the Chisago, Brule, Ontonagon, and Manitou units (fig. 2).

This model for the Midcontinent Rift is based on the modern East African Rift (Rosendahl, 1987). In plan view the fundamental unit in the Gregory Rift is a parallelogram with lengths on the order of 50 to 70 km (maximum 190 km), and widths from 20 to 40 km (maximum 70 km). Length to width ratios vary from 2 to 4 with an average of 3. In cross-section the fundamental unit is commonly triangular, defining a half-graben. Because of this half-graben geometry, the width of any one rift unit is a function of its degree of uplift and erosion. When the half-graben is initially developed, it is bordered on its deep side by a major curvilinear, normal, listric fault system, and on the shallow side by a monocline, or series of normal, small displacement step faults. The fundamental unit is bound on its ends by complex structures striking obliquely to the rift axis, and include interbasinal highs, ridges, and regions of uplifted basement. Igneous and sedimentation wedges of alternating isopach patterns distinguish juxtaposed rift units. These isopach patterns differ by being symmetric parallel, but alternating asymmetric perpendicular, to the trend of the rift axis.

The least mature of the Midcontinent Rift System zones appears to be the Maumee and Mackinaw zones (table 1). The Maumee zone displays a symmetrical, unfaulted, extensional basin associated with a simple gravity signature (Brown and others, 1982). The Mackinaw zone is similar, differing only in that the boundaries of this zone are associated with listric normal faults, none of which can be traced to the Moho discontinuity (Behrendt and others, 1988). The semi-mature Kansas zone consists of an asymmetric basin plunging to the west and bounded by normal faults (Berendsen and others, 1988; Serpa and others, 1984). The Iowa zone is identified primarily by strong gravity-pattern changes. An east-west seismic line in central Iowa is inconclusive regarding basin symmetry; and appears as a central horst associated and bounded by reactivated faults, one of which can be traced to a depth of 20 km (Chandler and others, 1989). The horst may be a consequence of two opposed funda-

mental units. These faults suggest compression, and may reflect a greater maturity than the Maumee, Mackinaw, and Kansas zones.

The Superior zone is the most mature in the Midcontinent Rift System (McSwiggen and others, 1987), and is recognized by disrupted gravity trends, crustal separation of 50 km, a central horst bounded by reverse faults, and gabbroic intrusions. If the fundamental rift unit concept is a necessary constituent of modern and ancient rift evolution, then such fundamental units should be recognizable in the Lake Superior basin. Four such units can be identified, average 150 km in length by 60 km in width, for a length/width ratio of 2.5.

Structural sub-division of the Superior zone may apply elsewhere along the trend, however the increased depth of burial of the rock units in both directions away from the Lake Superior area and the limited distribution of geophysical data along the rift do not permit such detailed second-order differentiation.

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Table 1. Zone and unit differentiation terminology of the Midcontinent Rift System and associated geologic features.

MAUMEE Zone	Sag basin on COCORP seismic lines McClure #1-8 Sparks well stratigraphy	1st Order Accommodation Structure (Thiel Fault)
1st Order Accommodation Structure	Gravity "dogleg", Montcalm Co., Michigan First Seismic Corp. seismic interpretation	MANTOU Unit
MACKINAW Zone	GLIMPCE line F extension faulting McClure #1 Beaver Island test Amoco St. Amour #1-29 test and seismology Coalescing of MRS structure	2nd Order Accom. Structure
1st Order Accommodation Structure	Thiel Fault previously identified Fault break on GLIMPCE line G Major change in MRS strike Interrupted gravity and magnetic patterns	ONTONAGON Unit
SUPERIOR Zone	STRUCTURAL DETAIL →	2nd Order Accom. Structure
1st Order Accommodation Structure	Interrupted gravity and magnetic patterns Granitic intrusions, southeast Minnesota Belle Plaine (transform?) Fault System Borehole and gravity control, Blakeley Co., Minn.	BRULE Unit
IOWA Zone	Identified IOWA central horst structure Presence of extension and compression faulting Amoco #1 Elsie test and stratigraphy Regional well control	2nd Order Accom. Structure
1st Order Accommodation Structure	Broken gravity and magnetic trends Granite terrane, southeastern Nebraska Local well control South-Central Magnetic Lineament	CHISAGO Unit
KANSAS Zone	Extension faulting on COCORP seismic lines Asymmetric central graben Texaco #1 Noel Poersch test and stratigraphy	1st Order Accommodation Structure (Belle Plaine Fault)

A = DECREASING RIFT MATURITY

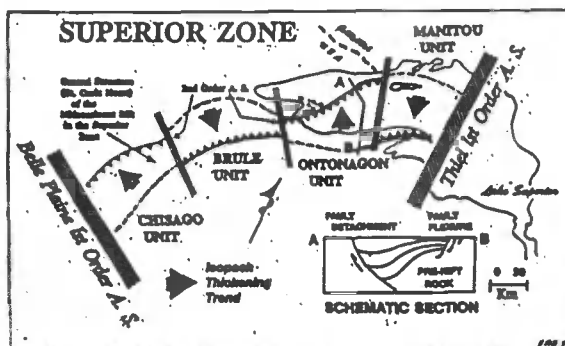
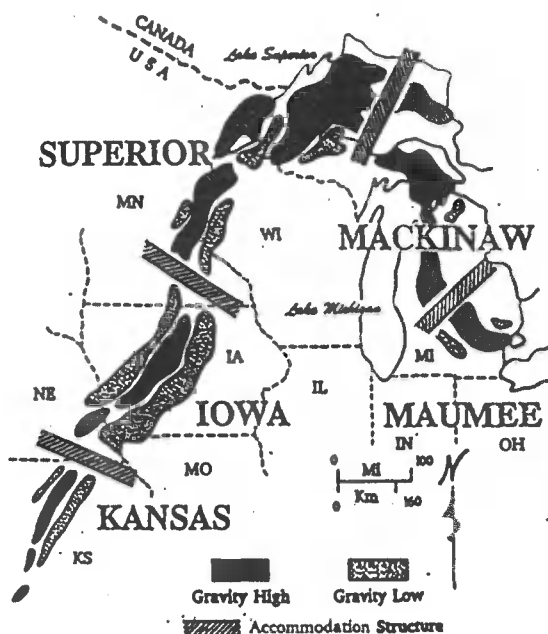


Figure 1. Location of accommodation structures and names of principal rift zones.

Figure 2. Details of the Superior Zone showing the location, names and polarity of fundamental rift units.

**STRUCTURE OF THE MIDCONTINENT RIFT SYSTEM
FROM 8-SEC REFLECTION SEISMIC DATA IN WESTERN LAKE SUPERIOR**

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ABSTRACT

Structural style and major features of the Midcontinent Rift System (MRS) in western Lake Superior interpreted from sparse seismic data by GLIMPCE have been confirmed by recently made available proprietary 60-fold, 8-sec CDP seismic reflection data and gravity and magnetic anomaly data (see McGinnis and others, this volume). Two new reflection profiles east and west of GLIMPCE line C disclose a deep asymmetrical central graben; however, the new lines define a southward thickening sedimentary-volcanic wedge in contrast to line C, suggesting complexities in structural blocks between major MRS rift zones. A broad arch near 47° 20' N., 90° W with a relief of many kilometers on the long, northeast trending reflection line in the west arm of Lake Superior is overlain with slight angular unconformity by Middle Proterozoic sedimentary strata, suggesting that the western arm of Lake Superior may in fact include at least two rift subzones. A broad syncline northeast of Bayfield Peninsula is bounded on the south by a fault. Whether this is a continuation of the Douglas Isle-Royale Fault System is not clear.

This work was supported by the U.S. Department of Energy, Office of Energy Research, under Contract W-31-109-ENG-38.

METAMORPHISM AND POLYGENESIS OF ORE DEPOSITS: AN EXAMPLE FROM THE MADEM LAKKOS PB-ZN-AG-AU DEPOSIT, GREECE

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Economic geologists frequently encounter difficulties in applying simple, single-event genetic models to complex ore deposits. This has invariably led to opposing camps of geologic thought which stubbornly argue that specific ore deposits, and even entire classes of ore deposits, are either 'syngenetic' or 'epigenetic', etc., and that these deposits formed by a single process during a single geologic event. This type of thinking ignores the fact that ore deposits, like all other rocks, have long and complex histories. They are subject to regional and local metamorphic and/or deformational events, magmatic intrusion, and the effects of interaction with circulating fluids of extremely variable chemistry. These processes can profoundly change the morphology and composition of any rock type, including those containing economic minerals. The recognition of multiple processes or events leading to the formation of economic mineral deposits, i.e. the concept of 'polygenesis', can lead to a much better understanding of not only complex and poorly-understood ore deposits, but also those that 'appear' to be simple. The problems and seeming contradictions encountered in applying single-event genetic models can often be avoided.

The Madem Lakkos deposit in northern Greece serves as an excellent example of a polygenetic ore deposit. The Madem Lakkos ores are hosted in marble of the Mesozoic(?) Kerdylia Formation, a high-grade metamorphic complex composed of migmatitic biotite gneiss interlayered with marble, hornblende gneiss, and amphibolite. The Kerdylia Formation is intruded by a variety of syn- and post-tectonic intermediate to felsic intrusions of Tertiary age. Long-believed to have formed as an epigenetic replacement body related to Tertiary magmatism, recent research has recognized the presence of three different and distinct ore types in the Madem Lakkos deposit that require a much longer and more complex genetic history.

Based on ore mineralogy, textures, and geochemistry, the Madem Lakkos ores can be characterized as either 1) Massive Sulfide Ore, 2) Replacement Ore, or 3) Skarn Ore types. Massive pyrite-sphalerite-galena ore exhibits abundant and well-developed metamorphic textures that indicate the ore has been metamorphosed to at least 600°C (amphibolite grade), together with its marble and gneiss host rocks. These textures include foliated/lineated galena and

sphalerite, slip and deformation twinning in galena and sphalerite, and granoblastic annealing/recrystallization features in galena, sphalerite, and pyrite with the development of 120° triple-point junctions. In spite of its metamorphism, the ore preserves a generally stratiform nature, a stratigraphic association with other chemical sediments, primary compositional layering, and metal zonation that are consistent with formation as a carbonate-hosted, syndepositional massive sulfide deposit.

Replacement ore consists of complex veins and manto-type impregnations in altered marble composed of pyrite, sphalerite, galena, tennantite, chalcopyrite, arsenopyrite, seligmannite, boulangerite, and minor amounts of a wide variety of additional sulfosalt minerals in a quartz-sericite-manganiferous carbonate gangue. Replacement ore cross-cuts and has reacted with the massive sulfide ore, and does not exhibit evidence of metamorphism. Euhedral zoned crystals with mineral and fluid inclusions, open space fillings, and complex textural relationships are characteristic of this ore type, and suggest replacement of marble by reaction with hydrothermal solutions. Replacement ore is enriched in As, Cu, Bi, Sb, Mn, Sn, and Te with respect to the massive sulfide ore, and was deposited from near-neutral pH solutions at temperatures ranging from 200 to 400°C. Preliminary lead isotope data indicate that massive sulfide and replacement ores have a common homogeneous lead source.

Skarn ore contains pyrite, chalcopyrite, minor amounts of other sulfide and sulfosalt minerals, and scheelite in a calc-silicate gangue assemblage of garnet, diopside, calcite, quartz, epidote, and minor chlorite and magnetite. Textures similar to those found in the replacement-type ore and an absence of metamorphic features are characteristic of the skarn ore. Fluid inclusions indicate a magmatic source and high temperature, low pressure deposition for the skarn ore. Skarn ores do not exhibit a clear spatial relationship to foliated aplitic igneous rocks in the mine, and appear to represent a distal skarn, related to co-regional intrusions but formed by hydrothermal replacement of marble at some distance from the source magma.

A multi-stage genetic model is proposed for the Madem Lakkos deposit. Synsedimentary massive sulfide ore was deposited as a stratiform body within a sequence of Mesozoic(?) shallow water platform carbonate, clastic/volcaniclastic, and evaporitic sediments. This ore and its host rocks were metamorphosed to upper amphibolite grade during Tertiary age regional metamorphism. Post-tectonic intrusion of the Stratoní granodiorite into the

metamorphosed Kerdylia Formation generated heat and magmatic fluids that produced skarn mineralization and a continuing convective hydrothermal system that mixed with meteoric waters, extensively altered the marble, and formed the replacement ores in part by reaction with and remobilization of the massive sulfide ore and in part by addition of constituents.

The Madem Lakkos deposit exhibits a distinctive variety of ore types whose combined features cannot be explained by a single genetic process. The mineralization cannot be characterized as simply 'syngenetic' or 'epigenetic'. It must be considered 'polygenetic', formed by a series of geologic events superimposed over an extended period of time. It is likely that other complex, enigmatic, and geologically controversial ore deposits have formed in similarly complex ways.

PETROGENETIC EVOLUTION OF THE PROTEROZOIC WAUSAU IGNEOUS COMPLEX, WISCONSIN
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The 1,520 m.y. old Wausau igneous complex is located in Marathon county, north central Wisconsin. It lies west of the Wolf River batholith and covers an area of roughly 300 km² (112 mi²). It is composed of two plutons, which are somewhat elongated to the northeast. The Stettin pluton, which lies to the northeast of the larger Wausau pluton, is elliptical and contains a core of nepheline and pyroxene syenite surrounded by syenitic rings. The subcircular Wausau pluton extends from north of Wausau, southward to west of Mosinee, and is separated into northern and southern segments by the Rib River lineament. The northern segment consists of Wausau syenites that grade into quartz syenite and the Ninemile granite, which forms the largest unit of the complex.

The Stettin pluton is a petrographically zoned intrusion characterized by tabular syenite in the wall zone, amphibole syenite in the intermediate zone, and pyroxene and nepheline syenites in the core zone, which show considerable textural variations. Perthitic alkali feldspar (50-90%), nepheline (7-25%), bluish-green sodic amphiboles (5-14%), aegerine-augite pyroxene (4-10%), constitute the major minerals in the Stettin rocks. Zircon, apatite, fluorite, calcite, magnetite, fayalite, biotite, and quartz occur as minor minerals.

The Wausau pluton also shows petrographical zoning with a wall zone of pyroxene-amphibole Wausau syenite with mechanically mixed xenoliths of quartzite and schist in a discontinuous but circular configuration. Xenoliths and mafic schlieren and clots are more frequent in the intermediate quartz syenite zone. Sodic plagioclase and microcline perthite (60-80%) and quartz (5-12%) constitute the major minerals and barkevikite, aegerine, fayalite, magnetite, and carbonate form the minor minerals. The Ninemile granite consists largely of porphyritic, medium-coarse grained, amphibole-biotite granite and a core of biotite-muscovite granite which possesses miarolitic cavities. Perthitic alkali feldspar (62-65%), plagioclase (5-7%), and quartz (21-29%) form the principal minerals with minor amounts of sodic amphiboles and biotite. Fluorite is an important accessory.

Electron microprobe studies of the principal phases indicate that the Wausau Igneous complex has mineral chemistry characteristic of anorogenic, alkaline (felsic) intrusions, as summarized in Table 1.

Chemically, the Wausau rocks show overall alkaline to subalkaline affinities (Table 2.)

Syenitization of volcanics at Stettin, miarolitic cavities in the Ninemile granite, the medium to coarse grained texture of the rocks of the complex, as well as the appreciable amounts of fluorite and other volatile-bearing minerals, suggest the presence of an active magmatic fluid phase during the crystallization and emplacement history of the complex. The Al content of the amphiboles and the relatively sharp contact relations with the wall rock are also indicative of epizonal emplacement, at depths of approximately 10-15 km.

The magma that formed the Wausau igneous complex was most likely generated in a crustal extension-thermal doming environment through partial melting of the Penokean crust. The initial stages may have involved dehydration melting of the mafic portions imparting the silica undersaturated characteristics represented at Stettin. The pervasive thermal doming may have caused progressive "softening" of the upper, less mafic, crust; thus changing the magma composition to silica oversaturation, as represented by the Ninemile granite. This process may have been aided by the limited assimilation of xenocrystic quartz. The apparent petrographic and chemical differences observed in the Wausau rocks are reflections of the progressive change

in the source rock and the degree of partial melting, and less the result of magmatic differentiation.

The Wausau igneous complex represents a magmatic event, related to the incomplete continental rifting of the early Proterozoic, with no apparent petrogenetic link to the Wolf River batholith.

Table 1. Mineral chemistry of the Wausau Igneous Complex.

Mineral		Fe/Fe+Mg	Compositional Phases
Amphiboles (Figure 1A)	Stettin	0.59-0.98	Ferroedenitic to ferro-hastingsitic hornblende, some riebeckite, arfvedsonite, and ferrichterite
	Wausau	0.76-1.00	
	Ninemile	0.91-0.99	
Biotites (Figure 1B)	Stettin	0.93-0.97	Annitic biotite
	Wausau	0.70-0.97	
	Ninemile	0.90-0.99	
Pyroxenes	Stettin	0.68-0.89	Aegerine (acmite)-augite
	Wausau	0.69-1.00	
Plagioclase Feldspars	Stettin	-	Albite-oligoclase
	Wausau	An ₀ -An ₂₁	
	Ninemile	An ₀ -An ₁₂	
Alkali Feldspars (x-ray data)	Stettin	Or ₃₅ -Or ₄₄	Microcline perthites
	Wausau	Or ₃₉ -Or ₆₄	
	Ninemile	Or ₅₂ -Or ₆₃	

Table 2. Chemistry of the Wausau Igneous Complex rocks.

Wt. %	Stettin	Wausau	Ninemile
SiO ₂	54.10-66.10	62.86-66.39	67.50-76.93
Na ₂ O+K ₂ O	10.20-13.80	11.20-12.59	9.46-11.01
Al ₂ O ₃	13.24-21.02	16.51-18.21	12.52-15.55
Zr (ppm)	100-1650	88-346	140-1500
Cl, F	0.01-0.35	0.01-0.22	0.06-0.14
Chemistry:	Alkalic-peralkalic	Metaluminous	Peraluminous-Metaluminous
	Nepheline Normative	Quartz Normative	Quartz Normative

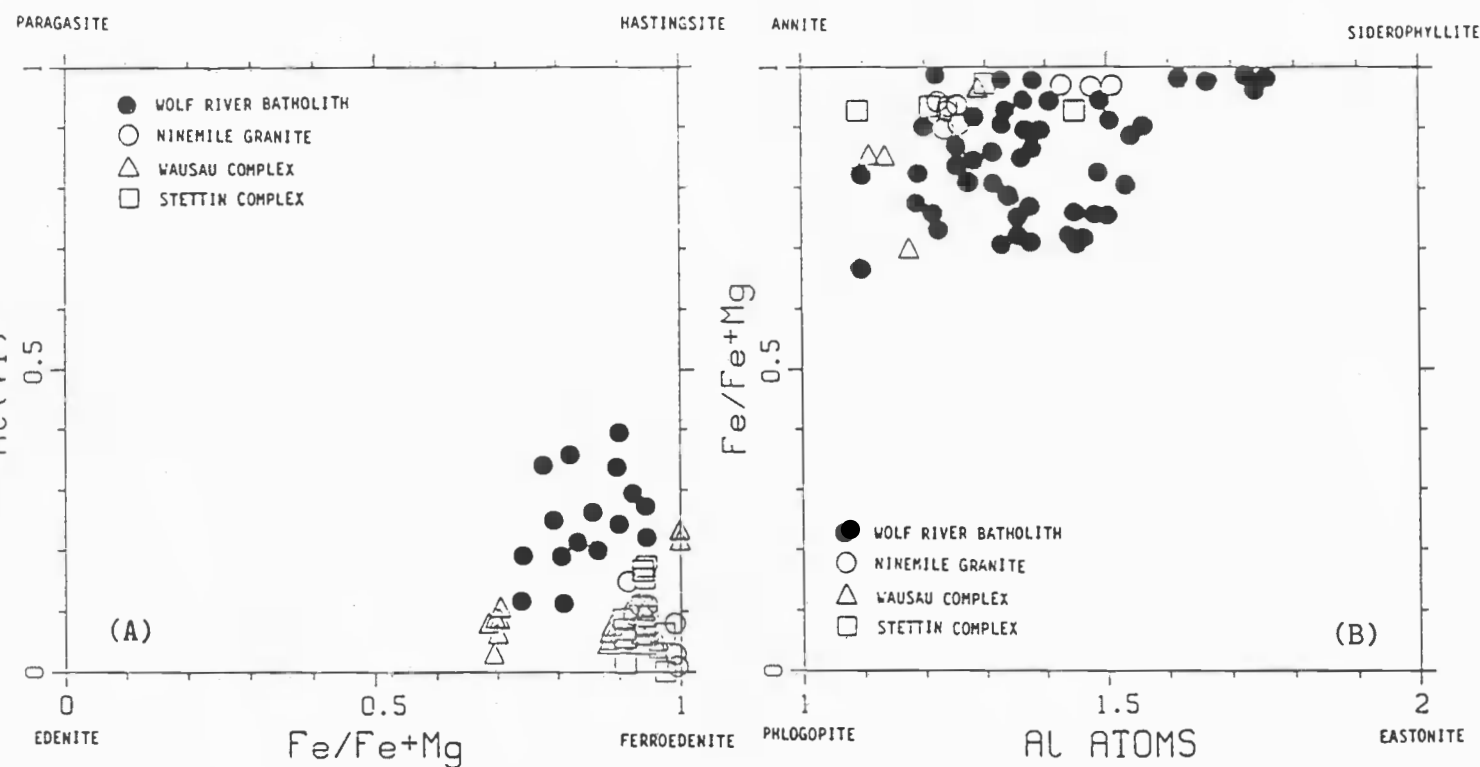


Figure 1. (A) Compositions of amphiboles from the Wausau Complex in terms of $Fe/(Fe+Mg)$ and $Al(VI)$. (B) Compositions of biotites from the Wausau Complex in terms of total Al and $Fe/(Fe+Mg)$.

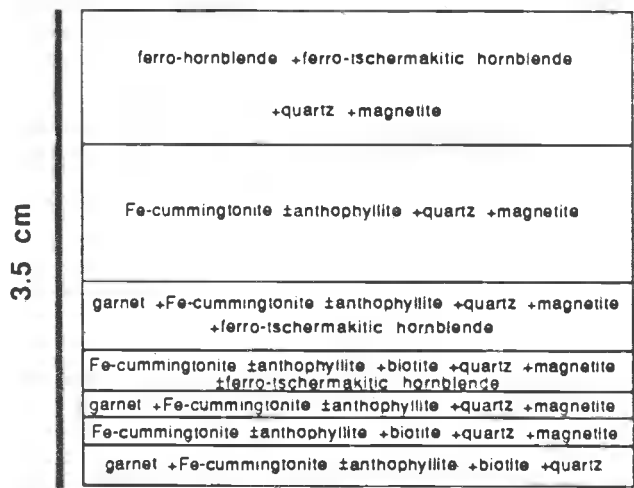
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PETROGRAPHIC AND MICROPROBE STUDY OF ISOLATED IRON-FORMATION LENS NEAR REPUBLIC, MICHIGAN: A SEARCH FOR HIGH-GRADE, PRE-PENOKEAN METAMORPHISM

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Though virtually all the iron-formation in the Republic Quadrangle of Marquette County, Michigan, is of Precambrian X age (Van Schmus and Woolsey, 1975), some isolated lenses of iron-formation occur within the mafic units of the Precambrian W age Bell Creek Gneiss (Cannon and Simmons, 1973). One of these lenses outcrops approximately one mile southwest of the village of Republic, Michigan, in the southeast corner of section 12, T.46N., R.30W. Samples from this outcrop were examined using petrographic and electron microprobe techniques to determine whether the mineralogy reveals evidence for an earlier, higher grade of metamorphism than that experienced by the Negaunee Iron Formation ~1.9 b.y. ago (Van Schmus and Woolsey, 1975). The unit is banded on the scale illustrated in the figure and includes zones of the following assemblages: ferro-hornblende + ferro-tschermakitic hornblende + quartz + magnetite, Fe-rich cummingtonite ± anthophyllite + quartz + magnetite, garnet + Fe-rich cummingtonite ± anthophyllite + quartz + magnetite + ferro-tschermakitic hornblende, Fe-rich cummingtonite ± anthophyllite + biotite + quartz + magnetite ± ferro-tschermakitic hornblende, garnet + Fe-rich cummingtonite ± anthophyllite + quartz + magnetite, Fe-rich cummingtonite ± anthophyllite + biotite + quartz + magnetite, and garnet + Fe-rich cummingtonite ± anthophyllite + biotite + quartz. A complex mixture of Fe-S phases is also present and associated with the magnetite. Garnet and amphibole compositions are virtually the same as those of the highest grade of the Negaunee Iron Formation (Haase, 1982) and biotite-garnet pairs yield paleotemperatures of ~535°C, compared to ~550°C for Negaunee Iron Formation rocks in the same vicinity (Haase, 1982). Though the higher-grade mineral, orthopyroxene, has been reported in some of these isolated lenses (Cannon and Simmons, 1973), our preliminary results suggest that there is no mineralogical evidence in this locality for an earlier metamorphism more intense than that experienced by the Negaunee Iron Formation.



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ONE, POSSIBLY TWO, IMPACT CRATERS UNDER DePERE, WISCONSIN, DISCOVERED VIA WATER WELL
LOGS AND DRILL CUTTINGS
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Water-well drillers in Wisconsin are required to send descriptions of rock units penetrated by their drills to the Wisconsin Geological and Natural History Survey. If the well is to be a "high-capacity" producer, they are required also to send in drill chips collected at 5-foot intervals. From the chips Survey personnel prepare detailed logs of the drill holes. These records, which have been accumulating since about 1900, are an extremely valuable source of information on subsurface geology.

My interest in impact craters began years ago when I started work on the Glover Bluff structure (1). This is now "officially" accepted as being of impact origin (2). The Rock Elm structure may also be (probably is, in my opinion) of impact origin (3)(4). Both structures appear to be of Lower to Middle Ordovician age.

There are plenty of Lower and Middle Ordovician sedimentary rocks in eastern Wisconsin. Several quarries near Lawrence University were begun in upper Middle Ordovician dolomites of the Sinnipee Group (5) and got down into Lower Ordovician Prairie du Chien dolomite as development progressed. Lower Middle Ordovician strata, mainly the St. Peter sandstone, are commonly thin in this area and may be missing altogether. In two of these quarries the St. Peter appears only as lenses a few meters thick. Near the bottoms of some lenses there are potato-size objects which superficially look very much like chert nodules but are quite different in details of external form and internal composition. I interpret them as impact bombs (6). In northern Illinois I found similar objects associated with small spherules that bear a close resemblance to silicified ooids. But these too are different internally from ordinary ooids. Some appear to have crystallized from glass in a manner similar to that of lunar glass spherules and the "microtektites" found in modern sea-floor sediments. I interpret them as impact spherules (7). The Illinois spherules have so far been found only in loose chunks of rock but there is good reason to believe that these chunks came from near the base of the St. Peter sandstone.

Since these initial discoveries I have found similar impact bombs(?) and/or impact spherules(?) of about the same age at a number of other locations in Wisconsin and in Arkansas, Pennsylvania, and Newfoundland. These widespread impact ejecta(?), plus the known Lower to Middle Ordovician craters or crater substructures, suggest that Planet Earth may have been hit by an unusually large number of asteroids or comets during this time interval.

It occurred to me that the actual abundance of craters of Lower to Middle Ordovician age might be much greater than the number of known craters now regarded as being of this age would indicate. And that it might pay to look for buried ones via logs of, and drill cuttings from, water wells. A buried crater formed near the close of Lower Ordovician time should be filled with an unusual thickness of Middle Ordovician sediment--in Wisconsin, St. Peter sandstone. Conversely, the Lower Ordovician (Prairie du Chien dolomite in Wisconsin), having been excavated during crater formation, should be thin or absent. Unfortunately, this criterion alone is an insufficient guide for buried-crater hunters since the Prairie du Chien, during a brief interval of emergence, suffered considerable erosion by surface and subsurface water, so that thick St. Peter overlying thin Prairie du Chien is likely to be found almost anywhere. An additional criterion must be applied: impact craters are excavations of limited, normally circular, extent; excavations produced by erosion are likely to be more extensive and irregular in shape. So the buried-crater hunter must look for thick St. Peter over thin Prairie du Chien in an area which is at least limited even if its shape cannot be determined from the information supplied by well logs. Even this criterion leaves open the possibility that the filled "hole" indicated by a definitely limited area of thick St. Peter over thin Prairie du Chien may simply be a sinkhole. This is always an alternative unless the bottom of the thick St. Peter goes well below the lowest level reached by holes likely to have been generated by solution: i.e., down into Cambrian sandstone or the Precambrian basement.

Proof that a buried hole of any kind was produced by impact would have to come from rock samples provided by drill cuttings. Impact cratering of any magnitude is accompanied by a good deal of melting and shocking of the target rocks. Evidence of one or both of these activities would have to be found in drill cuttings before anyone would believe that a buried hole, regardless of extent or depth of penetration, might actually be an impact crater.

Fortunately, Mai and Dott (8) have recently published maps showing (a) variations in the thickness of the St. Peter in eastern and southern Wisconsin, and (b) the stratigraphic age of the rock which directly underlies it. The maps are based on a study of nearly 900 "high capacity" wells logged by the State Survey from drill cuttings. From these maps anyone can easily pick likely locations for buried impact craters using the criteria outlined above. For starters, I picked the DePere area, one of a number of areas where the maps show that the St. Peter is unusually thick in a limited area and that its bottom cuts well down into the Cambrian. Also there is good "control" in that the area contains quite a few high capacity wells.

It was a lucky choice. Thin sections were prepared from drill chips provided by the State Survey and, sure enough, impact melt (glass, unaltered or partly crystallized) was found in a number of chips that came from near the bottom of the St. Peter. Some features noted in these small samples (averaging about 5 mm in diameter) are:

1. The melt glass is commonly red, often quite a dark red. This is a helpful feature to go by in selecting chips for sectioning.
2. Individual quartz sand grains, grain fragments, and bits of sandstone are commonly present. No convincing shock lamellae were found in the quartz but occasional grains and grain fragments have been converted to diaplectic glass. In fragments of sandstone individual grains may have been tightly squeezed together and some melting may have occurred at grain contacts.
3. In some cases the melt has crystallized completely to a mixture of large anhedral crystals of carbonate mixed with aggregates of smaller anhedral quartz crystals. Drill chips consisting of this kind of material are white.
4. In one section, abundant euhedral rhombs of carbonate are present in a matrix of red glass. They appear to be miniature phenocrysts.
5. Rounded granular aggregates of green, or rarely colorless, epidote are fairly common in red melt glass containing quartz sand grains.

In regard to the possibility that two, rather than just one, crater may be present under DePere: wells 4, 5 and 6 in Figure 1 almost certainly went through the bottom of a single crater. The maximum possible size of this crater is limited to the northwest, northeast, and southeast by Survey-logged wells Nos. 7, 3, 2 and 8. To the southwest its maximum size is limited by a cluster of wells for which only drillers' logs are available. In the middle of this cluster is another Survey-logged well, No. 12, where thick St. Peter sandstone rests directly on Cambrian as in wells 4, 5 and 6. This well definitely passes through a crater since cuttings from it contain an abundance of melt. There may be a separate crater here. If well 12 is in the same crater as wells 4, 5 and 6 the driller's log for well No. 19 must be regarded as inaccurate. Or at least misleading: the "lime rock" the driller reported under only 9 meters of sandstone could be a slide block.

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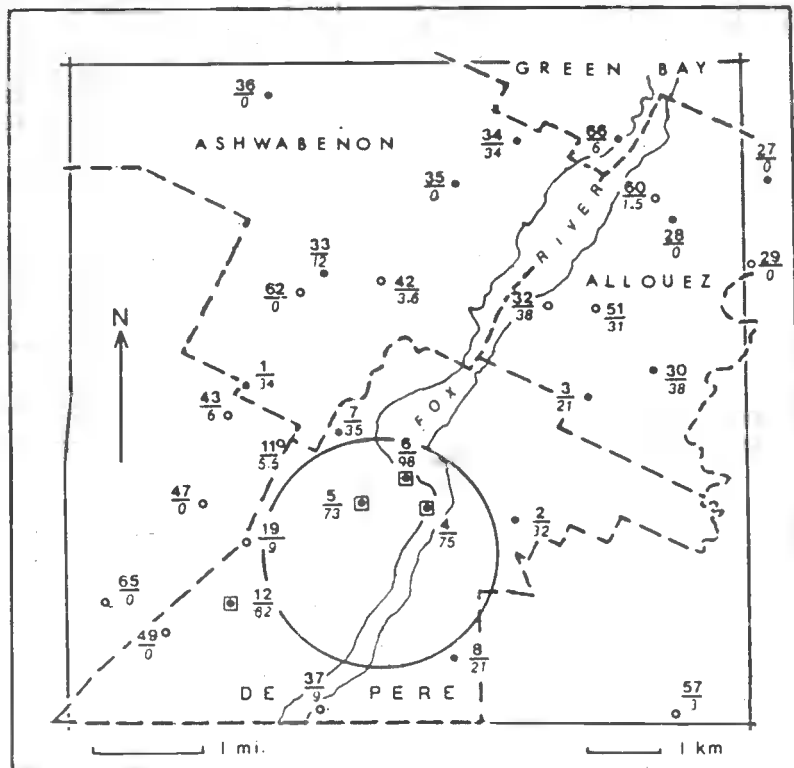


Fig. 1. Wells in T 23 N, R 20 E which pass through the St. Peter sandstone. North and east boundaries of the township are hypothetical since this area is occupied by old French land grants. Empty circles: wells for which only drillers' logs are available. Blacked-in circles: wells logged by the State Survey. Circles surrounded by squares: wells in which impact melt has been found. Upper figure adjacent to well: well number (arbitrary). Lower figure: thickness of St. Peter in meters. Large circle: maximum possible diameter of crater penetrated by wells 4, 5, 6 if driller's log for well 19 is reliable.

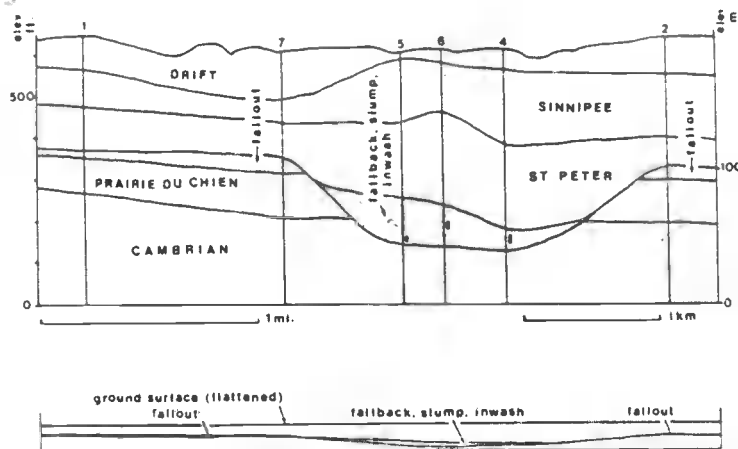


Fig. 2. Above: Cross section from well 1 to well 2 with data from intervening wells projected onto it. Vertical exaggeration x10. Dash marks adjacent to wells 5, 6, 4 indicate levels at which impact melt has been found. Presence of fallout hypothetical: drill chips from wells 1, 7, 2 have not yet been examined. Below: same cross section with no vertical exaggeration.

PRELIMINARY GEOMAGNETIC MODEL OF THE ST. CROIX HORST
IN POLK COUNTY, WISCONSIN

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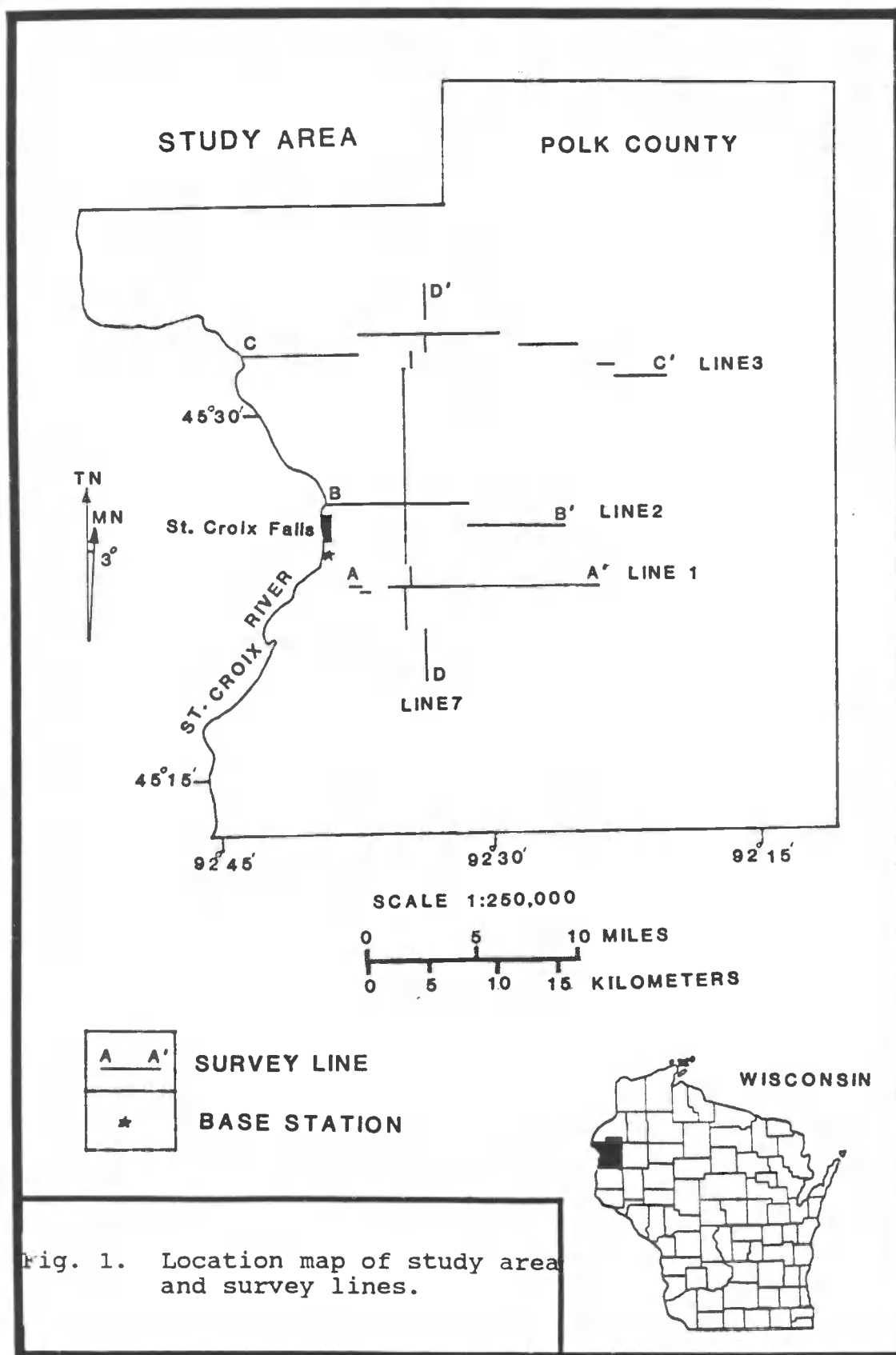
Total field Land magnetic data was collected in Polk County, northwestern Wisconsin, during June and July, 1989, in order to model the eastern portion of the St. Croix Horst and related volcanics. The St. Croix Horst, a major structural feature of the Midcontinent Rift System, outcrops in Polk County and trends northeast to Bayfield County, Wisconsin.

The study consisted of four survey lines totalling 60 miles (Fig. 1). Three lines traversed west to east, approximately normal to the horst. The fourth line traversed south to north, subparallel to the horst axis. Data was collected at 0.1 mile intervals. In general, field values are consistent with available aeromagnetic maps for the area. A magnetic relief of 3066 gammas was found in the area with a maximum value of 61576 gammas near the horst axis and a minimum value of 58510 gammas in the southeast part of the study area. Figure 2 shows the data contoured with a contour interval of 500 gammas. Magnetic susceptibilities, sampled from outcrops, range from 0.009 to 0.0003 cgs with an average value of 0.004 cgs. Values for total magnetic field intensity, declination and inclination used for modeling are 58640 gammas, 3 E and 73.5 , respectively.

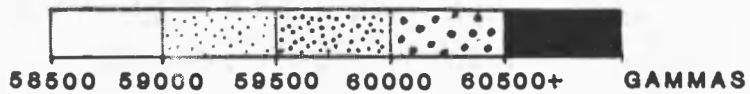
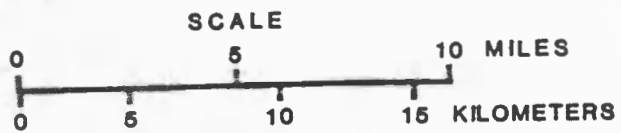
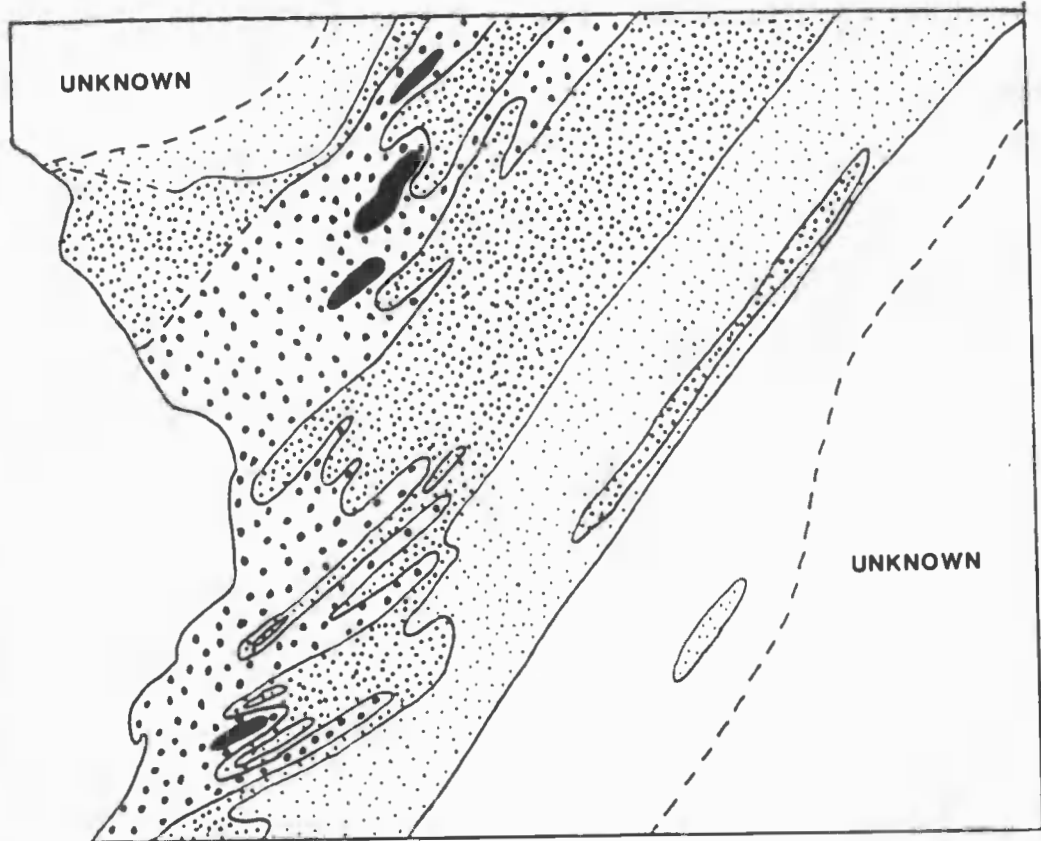
Preliminary modeling of the magnetic field data yields two models: 1) a rootless system where volcanics are 5 miles thick and susceptibilities are high and 2) a 7 mile thick volcanic sequence with low susceptibilities underlain by a deep central ultramafic root extending to 12 miles. Both models have half-graben structures on the eastern flank of the horst.

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MAGNETIC ANOMALY MAP



POLK COUNTY

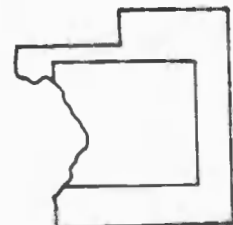


Fig. 2. Magnetic anomaly map for the study area.

A COMPARISON OF TWO ARCHEAN ULTRAMAFIC PYROCLASTIC ROCK UNITS, NORTHWESTERN ONTARIO

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Two ultramafic pyroclastic rock units occur 100 km apart on opposite sides of the Quetico fault along the southern margin of the Wabigoon Subprovince of the Superior Province. Detailed mapping, petrography, and chemical analysis have shown that these units may be correlated, as has been suggested by Howard Poulsen (pers. comm., 1988). The two units are:

- 1) The Dismal Ashrock which is located 4 km north of Atikokan and is part of the Steep Rock Group (Wilkes and Nisbet, 1988). This unit is 100 to 400 m thick and 10 km in length with excellent exposure in the former Steep Rock iron mine.
- 2) The Grassy Portage Bay Ultramafic Pyroclastic Rock Unit (GUP) which occurs 100 km to the west, along the eastern side of the Rice Bay dome, in an arcuate fold interference pattern 10 km long. It has a maximum thickness of 800 m.

Both units are delineated into sub-units based on physical volcanological parameters. The Dismal Ashrock is divided into lapilli tuff, volcanic breccia and pillowed flow. The GUP is divided into lapilli tuff and volcanic breccia. The lapilli fragments at each locale range from scoriaceous to non-vesicular and are magnetic. Two unusual fragment types were recognized at each location: 1. composite lapilli (lapilli-sized fragments consisting of multiple lapilli fragments in a rind of quenched lava) and 2. cored lapilli (lapilli fragments with a lithic core and a rim of quenched lava). Spinifex and skeletal crystals in these rims at the Steep Rock locality document their magmatic origin as opposed to formation by ash accretion. Accidental fragments of carbonate and tonalite are found within the Dismal Ashrock and one accidental carbonate fragment is found in the GUP.

The chemical composition of these two units shows a good correlation. Rock samples from the lapilli tuffs and juvenile fragments cut from rock samples are ultramafic; their SiO₂ content ranges from 40-46 wt.% and their MgO content ranges from 16-25 wt.% calculated on a volatile free basis. These samples plot within the komatiite field on a Jensen AFM diagram. However, they are much higher in total Fe and TiO₂ than those on a normal komatiite trend.

These data indicate that the Dismal Ashrock and the GUP are correlative. Shear zones at the top of the Dismal ashrock and on both sides of the GUP indicate that an early period of deformation, with some thrusting, may have occurred before late movement on the Quetico fault. This would have resulted in the splitting of an original ultramafic pyroclastic unit into the upper GUP and lower Dismal Ashrock.

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METAMORPHIC ZONATION IN THE NORTH SHORE VOLCANIC GROUP, MINNESOTA

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In the southern limb of the North Shore Volcanic Group (NSVG) a zonation of alteration minerals in the basaltic lava flows between Duluth and Tofte is observed (Fig. 1). Alteration minerals infill former vesicles and fractures and also replace early formed alteration minerals and igneous minerals. The main features of this zoning can be summarized as follows:

- 1) Metamorphic facies ranging from a lower actinolite-epidote-chlorite to an upper thomsonite-scolecite-smectite facies are observed. The following mineral associations are distinguished from top to bottom: thomsonite-scolecite-smectite, heulandite-stilbite-smectite, laumontite-chlorite, laumontite-prehnite-chlorite-(pumpellyite), epidote-chlorite-(pumpellyite), epidote-actinolite-chlorite.

This facies succession is consistent with a trend to higher temperature mineral assemblages with increasing burial depth.

- 2) The clear trend is disturbed by a recurrence in the area of the village of Little Marais. South of Little Marais the heulandite-stilbite-smectite zone, typical of the upper parts of the sequence, occurs apparently stratigraphically below flows of the laumontite-chlorite zone. Block tectonics can explain this recurrence.

Albitization of the basaltic flows is a main alteration feature. The albitization front is dependent on the stratigraphic position within the NSVG. Ca-rich plagioclase of the uppermost part of the sequence is not altered, even in the flow tops. With greater burial depth albitization becomes increasingly pervasive. In some flows of the laumontite-chlorite and higher metamorphic facies complete albitization is observed. Further, the albitization front in each flow is dependent on the permeability of the rock. Whereas the flow tops and bottoms of stratigraphically lower flows show almost complete alteration, the massive flow interiors remain unaltered. Massive flow interiors are only altered in a few, mainly thin flows in the stratigraphically lowermost part of the sequence, i.e., in flows displaying metamorphic grade from laumontite-chlorite up to epidote-actinolite-chlorite facies.

In addition to the zonation characterized by different mineral assemblages, a compositional zonation of the new formed albite replacing Ca-rich plagioclase is observed within the NSVG but also within single flows. The composition of the new formed albite displays a clear metamorphic zonation. In general, it can be said that in the upper part of the sequence albite shows compositions far away from that of ideal albite. In lower parts of the sequence, i.e., in flows with higher metamorphic facies, albite composition lies between 95 and 100 % mol Ab approaching that of ideal albite. Composition of the new formed albite also displays a

zonation within the flow itself. Albite in flow tops and bottoms of flows of all metamorphic facies lies always closer to stoichiometric composition than albite in more inner, less intensively altered parts of the respective flow.

The metamorphic zonation is furthermore recognized in the composition of the new formed phyllosilicates infilling amygdules and replacing mafic minerals, the stable isotopic ratios of alteration minerals, and the homogenization temperatures of fluid inclusions (SCHMIDT, 1989).

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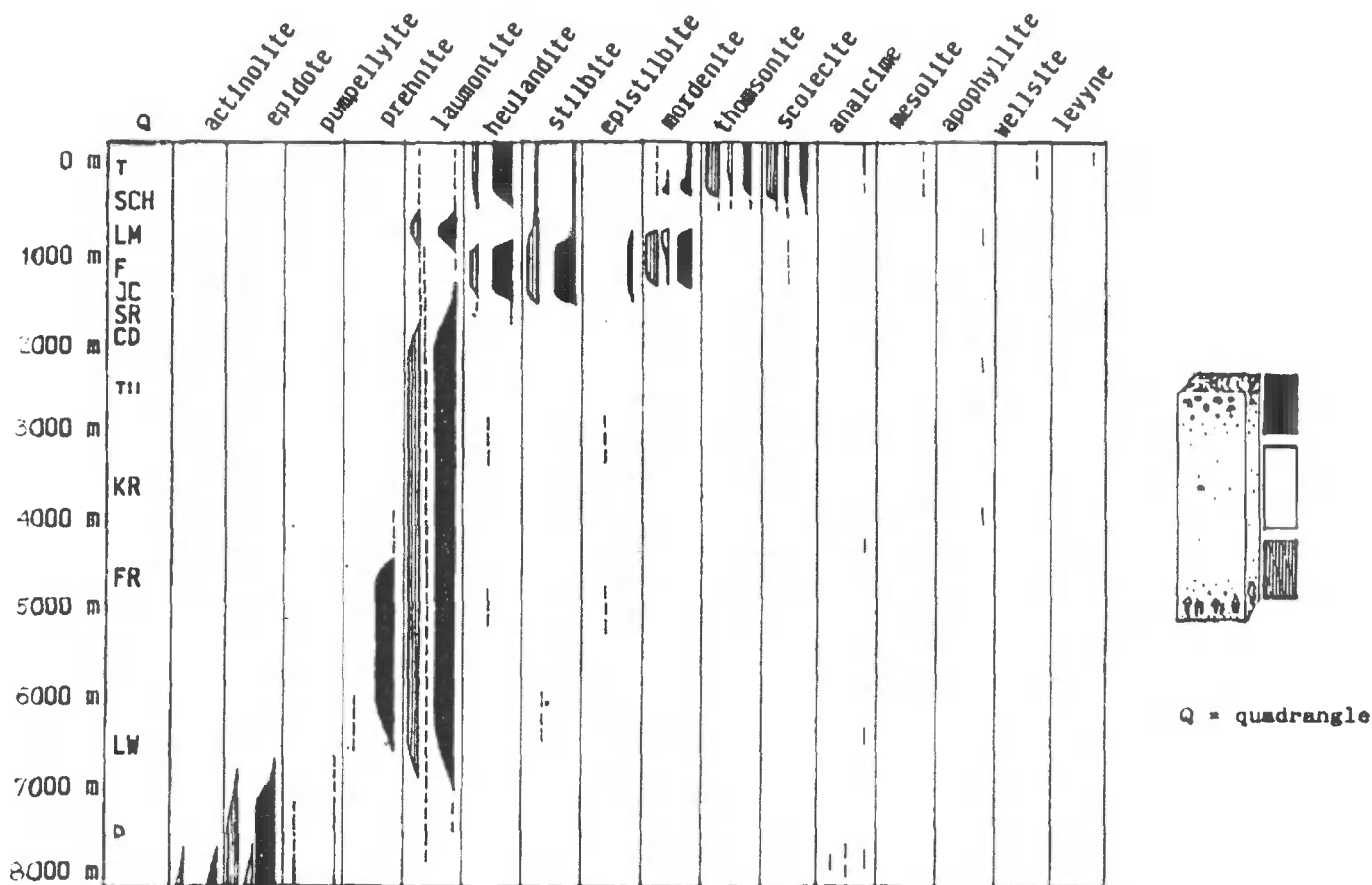


Fig. 1 Metamorphic zonation within the North Shore Volcanic Group. Sampling positions within the flows are indicated in the small sketch to the right. This figure is based on 280 thin sections, 258 Debye-Scherrer and 40 diffractogram analyses and microprobe analysis. The letters to the left side indicate the topographic quadrangle, e.g., D: Duluth, T: Tofte. Exact location of flows are given in SCHMIDT (1989).

Implications of Igneous Rock Geochemistry in the Penokean Orogen for
Metallogeny and Tectonic Setting:
A Synthesis of Recent Data

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Recent geochemical studies of igneous rocks in the Early Proterozoic Penokean orogen of the Lake Superior region provide important constraints on the tectonic evolution of the orogen and help to establish a basis for predictive metallogeny. The epicratonic Marquette Range Supergroup, which is north of the Niagara fault zone in upper Michigan, includes a bimodal tholeiitic basalt and lesser rhyolite volcanic suite having chemical characteristics (major and trace elements including REE's) typical of within-plate, rift-related magma types. The compositional characteristics of the volcanic rocks and results from recent studies of the sedimentary rocks support a rifted continental margin history for the northern portion of the Penokean orogen. The major iron formations of the Marquette Range Supergroup probably were deposited during the period of rifting before actual crustal separation, although some iron formations also may have been deposited during later evolution of a fore-deep basin.

The Wisconsin magmatic terranes occur south of the Niagara fault zone. The northern terrane, the Pembine-Wausau terrane, consists of widespread island-arc tholeiitic and calc-alkaline sequences that range from 1860 to 1880 Ma in age and an areally more restricted calc-alkaline suite that formed between about 1835 and 1845 Ma. Ophiolitic ultramafic and basaltic rocks, which include serpentinite, layered to massive gabbro, sheeted dikes, and boninite, are found along the Niagara fault zone and show that the fault zone marks the suture between the Superior craton and the Pembine-Wausau terrane. Collision along the suture probably occurred following a period of southward subduction at about 1860 Ma.

A southern terrane, the Marshfield terrane, contains remnants of mafic to felsic volcanic and plutonic rocks that range from about 1860 to 1890 Ma in age and an Archean gneiss basement. This terrane probably was accreted to the southern margin of the Pembine-Wausau terrane at about 1840 Ma following a period of northward subduction. The Eau Pleine shear zone in southern Marathon County, Wisconsin, appears to mark the suture zone between the terranes.

Base-metal massive sulfide deposits are present in the Pembine-Wausau terrane and appear to be restricted to a bimodal, calc-alkaline volcanic suite that is compositionally distinct from other volcanic units within the terrane. These compositionally distinctive high- Al_2O_3 - and light-REE-enriched, massive sulfide-hosting volcanic rocks may have formed in a within-arc rift. Their distinctive composition enhances the use of lithogeochemistry for massive sulfide exploration within the Wisconsin magmatic terranes.

Late to postorogenic (about 1835 Ma) and younger anorogenic (1760 Ma and 1470-1500 Ma) granitic intrusions and lesser amounts of rhyolite are locally abundant within the Penokean orogen, particularly in the southern portion of the Pembine-Wausau terrane and throughout the Marshfield terrane. These rocks range from calc-alkaline to alkalic in character. Minor molybdenum mineralization is associated with some intrusions, and other intrusions have anomalous Sn, Ta, Nb, U, and Th. In particular, a recently discovered 1733 Ma alkali-feldspar granite in the northern portion of the Southern Complex south of Humboldt, Michigan, is compositionally similar to rare-metal-rich granites of Nigeria and the Arabian Shield and suggests a potential for Sn-W (Ta-Nb) mineralization in upper Michigan.

THE MINERAL LAKE PLUTON: TWO INTRUSIONS RATHER THAN A LAYERED COMPLEX?

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INTRODUCTION

The Mineral Lake pluton is located near Mellen, Wisconsin, on the southern margin of Keweenawan exposures as part of the Mellen Complex (Aldrich, 1929; Leighton, 1954). The Mineral Lake and smaller Rearing Pond pluton, plus additional intrusive sheets of anorthositic gabbro and granite, form the western part of the Mellen Complex and are separated from the eastern part of the complex by the 1.0 - 1.2 Ga Mellen granite. The Mineral Lake pluton has been described as a steeply northward dipping 4.5 km-thick mafic layered complex intruded as a single magma with an anorthositic gabbro bulk composition (Olmsted, 1969). From the base up the pluton consists of roughly 1% ultramafic rocks, 10% anorthositic olivine gabbro, 73% gabbroic anorthosite and anorthosite, and 16% ferrodiorite (monzogabbro grading upward to quartz monzodiorite) and granite (Olmsted, 1969). The pluton has also been interpreted as forming from several magmas (Komatar, 1972) based on the occasional occurrence of poorly developed thin rhythmic layering in the anorthositic gabbro intrusion. It is here interpreted to consist of two separate intrusions; a lower anorthositic gabbro intrusion and an upper granitic intrusion.

Major and trace elements were determined on samples collected from both intrusions in the Mineral Lake pluton. Basal inclusions and adjacent older rocks were also sampled to determine their compositions as sources of possible contamination. Three plagioclase separates and one orthopyroxene separate were analyzed from the coarsely crystalline anorthositic gabbro intrusion. Major oxides were determined largely by X-ray fluorescence (XRF) and trace elements were determined by instrumental neutron activation analysis (INAA) and XRF. Some trace element and isotope data have been reported previously (Seifert et al., 1985).

The Anorthositic Gabbro Intrusion

The anorthositic gabbro intrusion consists of two zones with a thin basal chilled margin adjacent to older underlying country rocks. The basal chill zone grades upward into the anorthositic olivine gabbro zone which in turn grades upward into the gabbroic anorthosite zone. The gabbroic anorthosite zone volumetrically dominates the intrusion and the entire Mineral Lake pluton. The thin chill zone and the upper part of the thick gabbroic anorthosite zone contain basalt inclusions. Three plagioclase separates and one orthopyroxene separate were analyzed from this coarsely crystalline intrusion.

The Granitic Intrusion

The granitic intrusion consists of a lower monzodiorite zone and an upper granite zone with a gradational contact. The lower zone, in contact with the underlying anorthositic gabbro intrusion, is best described as a monzogabbro grading upward into quartz monzodiorite. The upper zone has the overall characteristics of granite, although the texture becomes granophyric locally. This intrusion is probably later than the anorthositic gabbro intrusion and is nearly conformable with the upper margin of that intrusion. The upper granite zone varies from coarse grained granular to granophyric in texture and is characterized by the dominance of K-spar and quartz over plagioclase. The granite and the K-spar-rich upper part of the quartz monzodiorite layer are both red and together they constitute the "red rock" portion of the granitic intrusion and the Mineral Lake pluton.

SUMMARY

The granitic intrusion is probably later than the anorthositic gabbro intrusion and was emplaced between the anorthositic gabbro and overlying rocks. The genetic relationship between the two intrusions is not known. Whereas the anorthositic gabbro was intruded as a crystal mush and shows little evidence for differentiation, the granitic magma exhibits the chemical and mineralogical trends expected of differentiation.

The presence of two intrusions of anorthositic gabbro and granitic compositions in the Mineral Lake pluton also explains the additional sheets of anorthositic gabbro and granite to the northwest of the pluton.

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MANGANESE POTENTIAL OF THE CRETACEOUS ROCKS FLANKING THE SIOUX RIDGE, MINNESOTA AND SOUTH DAKOTA

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Cretaceous strata in southwestern Minnesota and eastern South Dakota have lithologic, geochemical, and depositional attributes similar to those that host economic deposits of manganese at several localities around the world. Investigations are under way to determine if the conditions described in several depositional models (Cannon and Force, 1983; Frakes and Bolton, 1984; Force and Cannon, 1988), which have been proposed to explain these ores, existed in Minnesota and South Dakota, and if so, whether any anomalous manganese concentrations are present.

The models propose that a dilute ore-forming solution can develop in anoxic portions of stratified seas where iron is removed as pyrite, and where manganese concentrates to values up to 500 times those common in normal seawater. When this manganese-rich solution is transported to an oxygenated environment, such as along the margins of a depositional basin, the dissolved manganese precipitates either as an oxide or carbonate mineral species. Physical processes near shore may concentrate the manganese-rich material to yet higher grades.

In southwestern Minnesota and in adjoining parts of South Dakota, Upper Cretaceous strata were deposited along the eastern edge of the Western Interior Seaway on a gently sloping surface flanked by the Sioux Ridge, a quartzite highland which at times formed either a peninsula or a group of islands. Rocks of the Dakota Formation, Graneros Shale, Greenhorn Limestone, Carlile Shale, Niobrara Formation, and Pierre Shale define a shelf facies that passes into nearshore facies, such as the Split Rock Creek Formation along the Sioux Ridge paleocoast, and a regionally consistent lithostratigraphic succession of shallow marine and coastal sediments in Minnesota. Although decidedly more clastic, the Minnesota rocks correlate well with parts of the established Upper Cretaceous shelf sequence in South Dakota.

Two key components of the manganese depositional models have been observed in the study area. High-manganese/low-iron anomalies, although subeconomic, have been observed at several places in rocks deposited on an open shelf environment. These anomalies demonstrate that ore-producing solutions may have been periodically present in the seaway, and that at times, they flowed onto the eastern shelf. Secondly, strata reflecting cyclic oxic-anoxic conditions have been observed in both the nearshore facies and the shelf facies. This implies that anoxic flowpaths existed between anoxic parts of the basin, where manganese-rich solutions had

formed, and nearshore sites where oxic conditions favorable for ore formation existed.

This work was cofunded by the Minnesota Geological Survey, the South Dakota Geological Survey, and the Midcontinent Strategic and Critical Minerals Program of the U.S. Geological Survey.

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"STRATIGRAPHY" AND GENERAL GEOLOGY OF A PORTION OF THE
PARTRIDGE RIVER INTRUSION, DULUTH COMPLEX, MINNESOTA.

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Relogging of over 75 drill holes (~90,000 ft.) located along the northern (footwall) contact of the Partridge River Intrusion (T.58-59N., R.13-14W.) has indicated that the basal 3000 feet of the Troctolitic Series Rocks can be subdivided into at least seven major igneous units on the basis of rock type. Most of the units are continuous over an indicated eleven mile strike-length extending (NE to SW) from the Dunka Road Cu-Ni deposit to the Wyman Creek Cu-Ni deposit. Some of these igneous units appear to represent single cooling units in that they are floored by a bedded ultramafic member; whereas, other units contain abundant internal members reflecting continuous magma replenishment. Contacts between each of the units range from sharp to gradational, and pinch-and-swell thickness variations are common to all seven units. The relative spatial regularity of these units suggest that the Partridge River Intrusion (PRI) was intruded as several subhorizontal sheets that now exhibit dips of approximately 20 degrees towards Lake Superior (SE). However, some of the units also exhibit downcutting relationships and lateral "facies" changes indicating a complex intrusive history.

From the base up, these units are characterized by (Figure 1): Unit I sulfide-bearing augite troctolite with minor picrite to peridotite layers; Unit II - troctolite and augite troctolite with abundant picrite to peridotite layers and/or minor sulfide-bearing zones; Unit III - mottled textured anorthositic troctolite exhibiting a highly irregular olivine distribution; Unit IV - augite troctolite with a picritic base and grading upwards into; Unit V - coarse-grained anorthositic troctolite; Unit VI - augite troctolite to anorthositic troctolite with a picritic base; and Unit VII - augite troctolite with a well-bedded peridotite/picrite base. Field mapping suggests that an eighth unit (VIII) and possibly additional units are present above Unit VII. Unit VIII consists of troctolite to anorthositic troctolite with a well-bedded peridotite base. Anorthositic Series rocks are present in the extreme SE portion of the study area. Intrusive into Units I through VII are late-stage pegmatitic oxide-bearing ultramafic bodies. Geochemical samples for whole rock, trace element, precious and base metals, and rare earth element analyses have been collected from each of these units to: 1.) determine background elemental values for each of the major units and their members; 2.) determine if any vertical and lateral geochemical variation is present and to what extent; and 3.) determine if any lithogeochemical signature associated with each of the major units is present.

Establishment of an internal "stratigraphy" (within a sea of troctolitic rocks) of the PRI has provided an excellent opportunity to study the nature of any structural discontinuities present within both the basement and the overlying intrusive rocks. Cross-sections illustrating the internal "stratigraphy" in several drilled areas indicate that in both the Dunka Road and Wetlegs areas, numerous NE-trending normal faults parallel to the Midcontinent Rift are present. This supports the half-graben model of Weiblen and Morey (1980) which envisions a step-and-riser geometry at the

base of the Duluth Complex due to extensional tectonics. Also within the Wetlegs area, a NE-trending pre-Keweenaw(?) fault has been identified along which an inferred window of Biwabik Iron-formation is in direct contact with the PRI. Three oxide-bearing late-stage ultramafic bodies are also located along this zone which suggests that they may be genetically related to areas where massive iron-formation assimilation has occurred. Within the Wyman Creek area, no major structural discontinuities were located in either the basement or Troctolitic Series rocks. However, a downcutting relationship of Unit V into Units II and I is indicated at Wyman Creek.

During the course of collecting field geochemical samples, a mile long zone of modally laminated and cross-bedded oxide-bearing gabbro was located in what has previously been called the Colvin Creek Hornfels. Mineralogical and field relations suggest that the Colvin Creek body may actually be an intrusive unit that exhibits magmatic density current features. Field relationships also suggest that the Colvin Creek body is similar to the Powerline Gabbro which is exposed within about one mile to the northeast.

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Funding: Minerals Coordinating Committee
Minerals Diversification Plan

PARTRIDGE RIVER INTRUSION

11 MILES

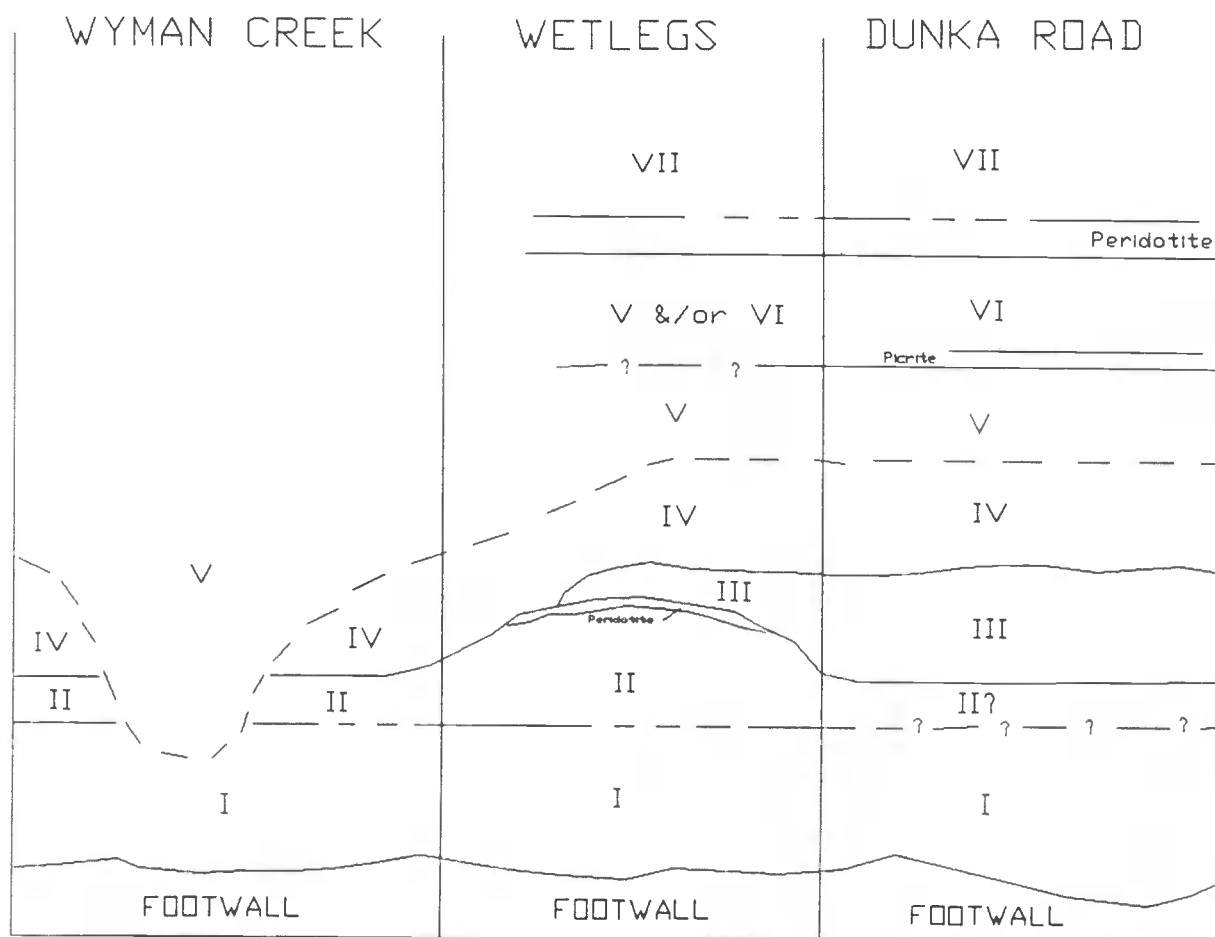


FIGURE 1: Strike-length correlation of major igneous units within the basal 3000 ft. of the Partridge River Intrusion.

UNITS: I = Sulfide-bearing augite troctolite, II = troctolite with picrite layers etc., III = 'Mottled' anorthositic troctolite, IV = augite troctolite, V = anorthositic troctolite, VI = anorthositic troct. to augite troctolite, VII = augite troctolite.

— sharp contact - - - gradational contact No scale implied.

NEW BEDROCK GEOLOGIC MAP OF PRECAMBRIAN ROCKS,
EASTERN LAKE SUPERIOR REGION, WISCONSIN AND NORTHERN MICHIGAN

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A new geologic map of Precambrian rocks in Wisconsin and northern Michigan (scale 1:500,000) has been compiled in cooperation with the Wisconsin Geological and Natural History Survey from published maps and available unpublished data. The map has 108 lithologic units.

The eastern Lake Superior region consists of 6 major Precambrian lithotectonic domains that record about 2,500 m.y. of geologic time. From oldest to youngest, these are (1) Archean gneiss terrane of northern Michigan and adjacent Wisconsin (2500-3650 Ma), (2) Archean greenstone-granite terrane of northern Michigan and adjacent Wisconsin (2700-2600 Ma), (3) a paired continental margin assemblage (Marquette Range Supergroup) and island-arc complexes (Wisconsin magmatic terranes), separated by the Niagara fault zone, of the early Proterozoic Penokean orogen, (4) central Wisconsin anorogenic granite-rhyolite (ca. 1760 Ma) terrane, (5) 1.47 Ga Wolf River rapakivi granite-anorthosite batholith, and (6) igneous and sedimentary rocks of the ca. 1100 Ma (Keweenaw) Midcontinent rift system.

The Archean gneiss and greenstone-granite terranes compose the basement of the Early Proterozoic passive continental margin assemblage; the boundary between the two basement terranes is the Great Lakes tectonic zone, a presumed paleosuture.

The Wisconsin magmatic terranes consist of at least two island-arc complexes. The northern (Pembine-Wausau) terrane is dominantly composed of tholeiitic and calc-alkaline volcanic rocks deposited in the interval 1860-1880 Ma, but contains a more restricted succession of calc-alkaline volcanic rocks deposited about 1835-1845 Ma. Granitoid rocks ranging in age from about 1870 Ma to 1760 Ma intrude the volcanic rocks. This terrane was accreted to the continental margin about 1860 Ma. The southern (Marshfield) terrane contains remnants of mafic to felsic volcanic rocks about 1860 Ma that were deposited on Archean gneissic basement, foliated tonalite to granite bodies ranging in age from about 1890 Ma to 1870 Ma, and younger undated granite plutons. Following amalgamation of the two arc terranes at about 1840 Ma, intraplate magmatism (1835 Ma) produced anorogenic and rhyolite alkali-feldspar granite that straddled the internal suture.

The 1760-Ma-anorogenic silicic-alkalic rocks of central Wisconsin were emplaced about 100 m.y. after culmination of the Penokean orogeny. Deep seated granitoid rocks were intruded within the Pembine-Wausau arc terrane approximately contemporaneously with the anorogenic magmatism to the south.

The Wolf River batholith (1470 Ma) constitutes the third successive episode of anorogenic magmatism in the region. It is one of the older intrusions of the 1.4 to 1.5 Ga transcontinental anorogenic province of North America.

The youngest tectono-magmatic activity in the region resulted in tholeiitic volcanism, layered mafic intrusions, and associated red bed sedimentation within the Midcontinent rift system about 1100 Ma.

**A Geological Investigation in Vicinity of the Volcanic-Plutonic Contact,
Northern Block of the Marquette Greenstone Belt, Michigan.**

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During 1988, 14 km² of the northwesternmost portion of the Marquette Greenstone Belt, located approximately 20 miles northwest of the city of Marquette, were geologically mapped at a scale of 1:9000. The geology of this area differs from the previous detailed geologic studies to the south and east in that it includes the contact between the volcanic and the bounding plutonic rocks. The average grade of metamorphism in the Penny Lake area is higher than to the south. The structure of the Archean units within the area is complex. Foliations indicate at least two periods of deformation, and the orientation of a pyroclastic unit and a gabbroic sill indicate the continuation of a kilometer scale fold which was first recognized to the south by Johnson et al (ILSG 1987). Mineralization in the Penny Lake area appears to be sporadic.

The Archean volcanic section in the Penny Lake area is composed of the Volcanics of Silver Mine Lakes and is lithologically similar to areas to the south and east, such as Johnson et al (ILSG 1987). The volcanic rocks are composed of pillowed basalts with minor interbedded iron formation and pyroclastic-sedimentary units. The volcanic section is intruded by Archean gabbro sill-like bodies and rhyolite dikes.

The Archean plutonic section in the Penny Lake area has been divided into four different types. The oldest two have been subdivided into a gneiss unit based on a distinct gneissic fabric and a massive unit which correlates with the Granodiorite of Rocking Chair Lakes of Johnson et al (ILSG, 1987). Both the gneiss and massive units are quartz monzonite to granodiorite in composition. The age relationship between these two units is uncertain; in a broad sense, they may represent a single, extended plutonic event. The contact between these units and the volcanics is gradational, xenoliths of basalt exist near the margins of the intrusions, and dike like bodies of the granitoid intrude the basalts. The third type of granitoid intrusion is granitic in composition and dike like in form. These granite dikes are common in the Penny Lake Area, and vary in thickness from under .5 meter to over 10 meters. They cut both the gneiss and the massive granodiorite, and are cut by quartz veins. The dikes have sharp contacts with the volcanics and are variably deformed. The fourth type of granitoid intrusion are four, stock-like bodies of diorite. These stocks are roughly circular in cross section, and have a maximum diameter of a few hundred meters. The volcanics are highly foliated near the margins of the diorite, but the contact between the two units is sharp. Their massive and unfoliated textures suggest they are late in the plutonic history. Neither granite dikes nor quartz veins cut the diorite stocks, further suggesting a late timing.

Metamorphic grade varies within the volcanic section of the Penny Lake area, depending on distance from the large quartz monzonite-granodiorite intrusives. The metamorphic facies were determined by textures in the field as well as by limited thin section observations. Facies changes were determined petrologically, by using the change in calcium content of plagioclase, the type and color of amphiboles, and the existence of pyroxenes. In general, the metamorphic grade increases gradually from south to north, except for a portion of the volcanic section along the eastern boundary where the grade increases abruptly from greenschist to amphibolite across a north-south trending fault.

Zones of relatively intense alteration and associated anomalous precious metal mineralization are restricted to small areas near faults. Alteration in these mineralized areas is most often characterized by quartz, carbonate, and sericite. Sulfides, including pyrite, chalcopyrite, and sphalerite, are commonly found in the altered rocks as small, disseminated grains. Specular hematite is often found associated with granite dikes located within altered zones. Twenty-two samples from throughout the area were assayed for gold. Eight samples contained anomalous values of greater than ten parts per billion, with a maximum assay value of 274 ppb.

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

AIRBORNE GEOPHYSICAL SURVEYS OF THE EFFIE-COON LAKE COMPLEX, MINNESOTA

BY

Bruce D. Smith, Victor F. Labson, Robert J. Horton

A program to improve airborne geophysical data acquisition and interpretation has been implemented by the USGS Branch of Geophysics. The Effie-Coon Lake area is one of four areas chosen to test new geophysical methods to map geologic features favorable for buried mineral deposits. Airborne geophysical applications are particularly important since glacial and Quaternary sediments cover 95% of the bedrock in the area. This presentation describes preliminary results from two new airborne EM systems and from new total field magnetic data processing.

The Effie-Coon Lake study area, located in north-central Minnesota, is a 2.7 billion year (Ga) Precambrian terrain consisting of the Effie granitic intrusive complex and the Coon Lake zoned intrusive surrounded by metasediments and metavolcanics. The zoned intrusive, thought from limited outcrops and shallow drilling, to be mainly quartz monzonite is defined mostly from aeromagnetic data. A NW-SE trending 2.1 Ga mafic dike system, interpreted from aeromagnetic maps, intrudes the metamorphic sequences and intrusive complexes. Several different types of mineral deposits could be present in the area including base metals, gold, and platinum group element (PGE) deposits. Advanced airborne geophysical methods are needed to identify subtle geologic features favorable for buried mineral deposits.

The two new electromagnetic (EM) systems could be effective tools for regional and detailed three dimensional mapping of electrical resistivity. In general mapping of electrical properties provide complementary information to aeromagnetic and radiometric surveys. The two EM systems map shallow and deep resistivity variations. The shallow penetrating system, termed VLF for Very Low Frequency, measures EM fields generated by distant Naval communication stations at about 25,000 Hz. Unlike commercial VLF instrumentation, the components measured by the USGS system are used to compute apparent resistivity maps. The deeper penetrating system developed by the Branch of Geophysics measures the effect of magnetic fields generated by power lines at 60, 180, and 300 Hz.

Apparent resistivities computed from the VLF data average 300 to 400 ohm-meters with some areas as high as 1000 to 2000 ohm-m and as low as 10's of ohm-meters. High resistivities are a guide to locating shallow or exposed resistive bedrock which is helpful in geological mapping. Narrow resistivity

highs not associated with bedrock trends are in part due to glacial features such as eskars which contain gravels. The Effie complex is characterized by high apparent resistivities (>400 ohm-m) which may help to define boundaries of the intrusive which are not clearly defined by the gravity or magnetic data. Areas of low resistivities can be attributed to either thick glacial till or conductive shallow bedrock (for example graphite in metasediments).

The airborne EM instrument which measures magnetic fields generated by power lines has a depth of penetration is approximately ten times that of the VLF system and has a deeper depth of penetration than most commercial systems. Thus the system is much more sensitive to variations in bedrock resistivity than the VLF system. The measurements are processed to enhance mapping of conductive bedrock features which may be buried at depths of hundreds of meters. Important conductive bedrock features in the study area are mainly graphitic units in the metasediments. The distribution of these units is useful in understanding bedrock stratigraphy and structure. In addition, some conductive anomalies could indicate massive metallic mineralization.

The VLF and power line EM methods do not require an airborne transmitter, which greatly reduces the complexity, weight, and cost of the systems. Successful development and application of methods described in this study is a critical step in development of electrical methods that can be routinely used to complement other airborne geophysical data such as magnetic and radiometric measurements.

The airborne survey also includes standard total field magnetic data which combined with older (1984) USGS data yields an effective flight line spacing of 1/8 mile. A number of different standard enhancement methods used on the magnetic data include: a) color shaded relief, b) trend filtering, and c) boundary estimation. In addition a relatively new method of enhancement using a terracing operator has been applied to the data. This operator produces maps with boundaries showing terrains with different estimated relative susceptibilities.

All of the geological and geophysical data are being used in an integrated interpretation of the bedrock geology. Digital terrain, shown as color shaded relief, is being used to analyze possible surface expressions of bedrock geology. Final integrated interpretation makes use of a Geographic Information System (GIS).

GEOLOGY OF THE WEST DEAD HORSE CREEK DIATREME-HOSTED RARE METAL OCCURRENCES, SCHREIBER-HEMLO DISTRICT, ONTARIO

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The Dead Horse Creek complex consists of five separate diatremes located immediately west of the Middle Proterozoic Coldwell alkaline complex (Sage, 1982). The West Dead Horse Subcomplex diatreme occurs in strongly foliated Archean metasedimentary and metavolcanic rocks, is approximately 80 by 40 m in size, and contains three main, highly radioactive, mineralized zones: (1) eastern pits, (2) eastern extension, and (3) western pits. The eastern pits and eastern extension are situated in the main diatreme which is composed predominantly of monolithic breccia with hematized clasts set in a carbonate-rich matrix that also contains riebeckite. The western pits are situated west of the main diatreme on a narrow, mineralized structure striking at 130° , oblique to the host-rock foliation. Here mineralization is hosted in a silicified, hematized, carbonate-rich rock. Although the metal associations and mineralogy of the three zones are broadly similar (enriched in Zr, REE, Th, U) significant local variations exist, particularly in the nature and distribution of the REE-bearing minerals: the western pits are characterized by high values of Be (up to 0.62 wt.%), Sc (up to 250 ppm), Zr (up to 11.6 wt.%), REE (up to 1250 ppm), Th (up to 0.52 wt.%) and U (up to 0.31 wt.%). In contrast samples from the eastern pits and eastern extension contain lesser, but nevertheless significant abundances of Be (up to 240 ppm), Sc (up to 85 ppm), Zr (up to 2.8 wt.%), Th (up to 0.15 wt.%), and U (up to 0.08 wt.%); subequal amounts of REE (up to 1220 ppm); and are enriched in P_2O_5 (up to 2.46 wt.%) and Y (up to 235 ppm). In addition to zircon (often hydrated), complex Ca-Zr-bearing silicates and thorite, phenacite occurs in the western pits, and monazite and xenotime are found in the eastern pits and eastern extension. Chondrite-normalized REE distributions emphasize the variability of the REE-mineralogy (western pits, HREE-enriched, $La/Lu_N = 0.09$; eastern pits, LREE-enriched, $La/Lu_N = 9.1$ to 17.6). None of the mineralized samples have a marked negative europium anomaly, which suggests that the mineralizing fluids were oxidised.

MULTIPLE ARCHEAN TERRANES IN SW MINNESOTA - THE OLD GRAY
GNEISS SHE AIN'T WHAT SHE USED TO BE

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Major aeromagnetic and gravity lineaments that trend more or less parallel to the Great Lakes Tectonic Zone (GLTZ) subdivide the Archean gneiss terrane of southwestern Minnesota into three blocks that have distinctive geophysical characteristics. The block-bounding lineaments are the surface traces of north-dipping zones of planar structures; therefore they are approximately parallel to the GLTZ in three dimensions, not just in map view.

The northernmost block boundary, about 40 km south of the GLTZ, has been named the Appleton geophysical lineament. It separates the Benson block on the north from the Montevideo block on the south and, on the basis of sparse drilling, appears to be a zone of ductile shear and faulting that has been invaded locally, and synkinematically, by sheets of muscovite leucogranite. As judged from geophysical anomaly patterns and drilling data, the Benson block consists dominantly of granitic to tonalitic intrusions into gneissic wall rocks. The plutons range from strongly synkinematic to post-kinematic, and the block as whole may be a granitoid intrusive complex analogous in style to the Winnipeg River belt in the Superior Province of Manitoba and Ontario. The Montevideo block, in contrast, appears to be primarily gneissic rocks comparable to those exposed in the Minnesota River Valley between Montevideo and Granite Falls. The 3,600 Ma age component and granulite-facies metamorphism that characterize the Montevideo Gneiss have thus far not been documented in the Benson block.

About 45 km farther south, the lineament that separates the Montevideo block from the Morton block passes through Renville and crosses the Minnesota River in a zone of no outcrop between Granite Falls and Sacred Heart. A zone of faulting in this vicinity has long been postulated on the basis of earlier geophysical surveys and exposed small shear zones just north of the outcrop gap. Our data suggest that the fault zone is larger and more fundamental than previously thought, and imply that the Morton Gneiss and Montevideo Gneiss could well be separate and distinct elements of the Middle Archean crust that have been juxtaposed tectonically.

All three blocks of the Archean gneiss terrane are truncated geophysically on the east by anomaly patterns characteristic of Penokean plutons and, to a lesser extent, of folded supracrustal rocks. Similar but less diagnostic patterns flank the Morton block on the south and west, suggesting that the Archean gneiss terrane may be enveloped by Early Proterozoic magmatic belts. Scientific drilling to test these interpretations is underway and will continue.

This work was funded in part by the Minnesota Future Resources Commission.

Petrography and Sedimentation of The Middle Proterozoic
(Keweenawan) Nonesuch Formation Western Lake Superior
Region Midcontinent Rift Zone

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New information from drill hole logs, detailed sedimentological descriptions and petrographic analysis of Middle Keweenawan Nonesuch Formation in select Bear Creek drill cores from Bayfield and Douglas Counties Wisconsin, and examination of outcrops in northwest Wisconsin and Upper Michigan provide evidence for source rocks and environment of deposition (Fig. 1).

These data suggest that Lower Keweenawan volcanic units were the major contributors of detritus to the Nonesuch Formation in northwest Wisconsin, while Middle Keweenawan volcanics were only minor contributors. Sediment from Early Proterozoic and Archean crystalline rocks, although minor, increase in abundance upsection as older source rocks were unroofed.

Sedimentary structures and stratigraphic relationships suggest that deltaic processes, sheet floods, turbidity currents and suspension settling were the primary mechanisms of deposition in a lake with constant and perhaps rapid fluctuations in water levels brought on by changes in tectonism and/or climate.

The gradational contacts of the Nonesuch Formation with the underlying Copper Harbor Conglomerate and overlying Freda Sandstone, along with outcrop and drill facies data, suggest deposition of the Nonesuch on a prograding alluvial fan complex in the Midcontinent Rift Zone.

Examination of the genetic relationship of Nonesuch facies, combined with percentages of the different textural elements within each facies type, and petrographic data, suggest that deposition was generally from the south into the rift zone. Deposition appears to have occurred in a basin that was partially restricted, or perhaps completely isolated from areas containing Nonesuch Formation farther east in Wisconsin and Upper Michigan.

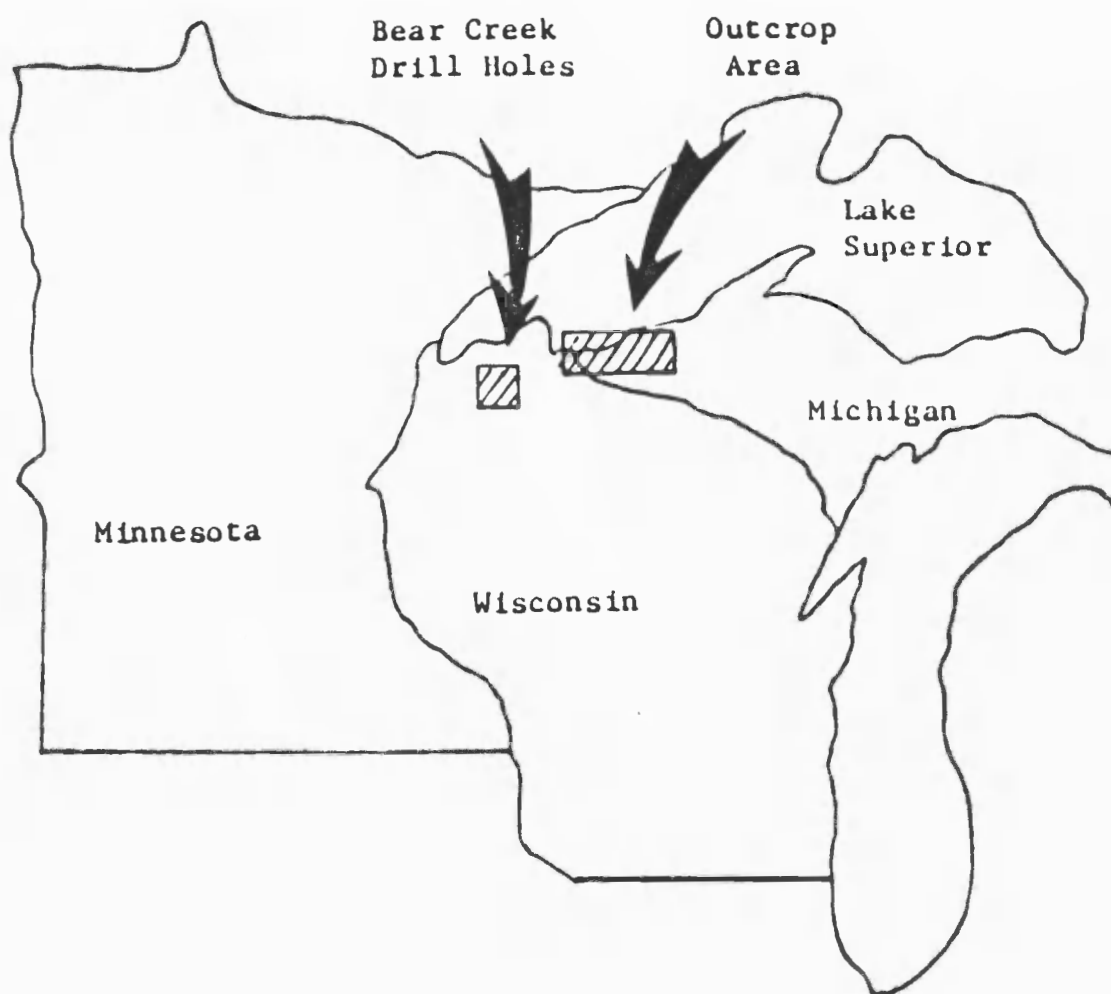


Figure 1. General location of outcrop and drill hole study areas.

GRAVITY AND MAGNETIC DATA OVER THE

WAUKESHA FAULT, S.E. WISCONSIN

by

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In the past few years gravity and magnetic data has been collected over the Waukesha fault in the southeastern corner of the state. The fault can be observed where it passes through a quarry in Waukesha. At this point it appears as a vertical fault with a displacement that has been estimated at between 30 (Mikulic and Mikulic, 1977) and 100 (Foley et al., 1953) feet. The displacement at depth is thought to be on the order of 1500 feet (Thwaites, 1957).

Initially, 1500 square miles of gravity data were collected on a one mile grid to investigate the linear extent of the fault. The resultant gravity signature is characterized by a zone trending N40E roughly three miles wide of tightly spaced contours. This signature extends for approximately 60 miles from the Lake Michigan shoreline near Port Washington to the southwest through Waukesha and on towards the Wisconsin - Illinois border. Gravity values on the northwest side of the fault are as much as 19 mgals higher than those to the southeast.

Our initial models of the fault based on the gravity data viewed it as a high angle growth fault downthrown to the southeast. The displacement was as little as 40 feet in the Niagaran dolomite near the surface to as much as 2000 feet in the Precambrian basement. In order to model the large gravity contrast across the fault it was necessary to include a high density mafic material at depth.

The gravity data was later supplemented by roughly 630 square miles of magnetic data taken on a one mile grid coincident with gravity stations. Magnetic readings varied between approximately 57,400 and 59,000 gammas. There is no clear linear feature evident in the magnetic data. Instead there are a number of roughly circular magnetic highs as much as 1300 gammas above and lows as much as 300 gammas below background levels. These features do not show any clear indication of the presence of a fault, rather they suggest individual intrusive bodies of relatively high susceptibility material and have been modelled as such. With this supporting information we are modifying our gravity model to incorporate a limited vertical fault consistent with previous views and individual mafic intrusives at depth.

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STRIKE-SLIP FAULTING IN ARCHEAN ROCKS IN THE VIRGINIA HORN
AREA, N.E. MINNESOTA: IMPLICATIONS FOR THE ORIGIN OF THE
VIRGINIA HORN STRUCTURE

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Field mapping in Archean metavolcanic and metasedimentary rocks in the Virginia-Eveleth-Gilbert area of northeastern Minnesota has revealed the presence of a significant strike-slip fault system, here called the Pike River System. In this area the fault system is composed of two major northeasterly trending faults connected by a series of more northerly trending en echelon strands. The configuration suggests a strike slip duplex.

Movement history along this system appears to have been complex. Although offset marker units have not been identified, map patterns suggest that early and possibly the most significant movement was sinistral. Kinematic indicators, however, indicate that (latest?) movement was dextral. In addition high angle slickensides associated with the duplex strands require a vertical component of movement.

The Pike River System trends along the axis of the Virginia Horn (the gentle anticline-syncline structure present in the unconformable superjacent Proterozoic rocks, so prominently outlined by the Z-shaped map pattern of the Biwabik Iron Formation), and most certainly exerted a controlling influence on its formation, although the Proterozoic rocks themselves have not been cut by these faults. It is here suggested that late dextral transpressional movement in the basement rocks, possibly a result of the Penokean collision to the south, created a compressional stress within the reactivated Pike River duplex structure, causing localized uplift of the basement rocks. The Virginia Horn structure is thus interpreted to be a drape structure over the uplifted basement rocks.

Mafic and Clastic Dikes as Keweenawan Paleostress Indicators in the Huron Mountains, Michigan

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The Huron Mountains of northwest Marquette County, Michigan, contain the pre-rift basement rocks closest to the northern apex of the Midcontinent Rift System (MRS) and thus are a strategic place to study paleostresses associated with the formation of the rift. This area is located astride the Trans-Superior Tectonic Zone (TSTZ) (Fig. 1), which bisects the arc formed by the two arms of the rift (Klasner et al, 1982). This zone lies parallel to the direction along which major crustal separation is inferred to have taken place across the rift. The study area in the Huron Mountains was mapped at a scale of 1:6000 so that the rocks and structures could be mapped and plotted in detail. The basement rocks of the Huron Mountains consist mainly of Archean granodiorite gneiss and amphibolite. The Upper Keweenawan (?) Jacobsville Sandstone overlies the Archean rocks nonconformably.

Structures in the Huron Mountains that reveal northern MRS kinematic patterns include 1) mafic dike swarms and basement rock joints, which record a pre- to syn-rift extensional cycle, and 2) aligned clastic dikes and joint sets in the Jacobsville Sandstone that suggest a post-rift compressional cycle. Mafic dikes in the Huron Mountains as much as 60 m wide have subophitic to diabasic textures and consist of plagioclase and clinopyroxene with subordinate amounts of opaque minerals. Dominant mafic dike trends are N-S and E-W, perpendicular and parallel to the rift axis, respectively (Fig. 2). Similar trends for mafic dikes in western upper Michigan were described by Baxter and Bornhorst (1988). Perpendicular dike trends are unusual in a rift environment; crustal extension ordinarily leads to a single set subparallel to the rift axis. Thus, the perpendicular dike pattern is presently somewhat enigmatic.

Seven vertical clastic dikes with a consistently NNE trend (Fig. 3) have been found within the Jacobsville Sandstone of the Huron Mountains. These aligned clastic dikes are as much as 20 cm in width, more than 100 m in length (they disappear beneath Lake Superior), and separated by as much as 2 km. Cathodoluminescence microscopy and petrographic analysis indicates that the clastic dike rock is a quartz arenite with well-rounded grains, both texturally and compositionally more mature than the wall rock, the Jacobsville Sandstone - primarily a feldspathic sandstone with conglomerate, siltstone, and shale members. Since the Jacobsville Sandstone rests nonconformably on crystalline basement rocks, it is unlikely that the clastic dikes were injected from below. An alternative is that the dikes are of the neptunian model - those that fill fissures from above. Outcrops of Jacobsville Sandstone are found as much as 150 m topographically higher than outcrops that display the clastic dikes. An explanation must, therefore, account for a stress state that permits the opening of extension fractures at a minimum depth of 150 m in the Jacobsville bedrock, the inferred minimum

pre-erosional thickness of the Jacobsville Sandstone in the Huron Mountains.

GLIMPCE reflection profiles A and F suggest the presence of reverse faults in rift-related rocks offshore from the Huron Mountains that may be an extension of the Keweenaw Fault. The NNE trend of the clastic dikes, parallel to the TSTZ, places them in an orientation parallel to the probable direction of maximum compression expected for the apex of the MRS during its compressional stage of development (Fig. 1). The trend of the clastic dikes nearly bisects the acute angle between two major sets of vertical joints in the Jacobsville Sandstone. These joints appear to represent a conjugate shear system, and the clastic dikes would thus correspond to the extension fracture position; a third set of joints parallels the dikes. Therefore, the aligned clastic dikes may have filled extension fractures formed parallel to a compression associated with the compressional stage of the MRS.

The compositional and textural maturity of the clastic dike rock in comparison to the Jacobsville Sandstone wall rock suggests that the dikes are composed of sandstone similar to that found in the Munising Formation (Upper Cambrian), a rock unit that overlies the Jacobsville Sandstone in slight angular unconformity in outcrops 60 km to the southeast of the study area. If the dike rock is indeed from the Munising Formation, then the clastic dikes provide a paleostress indicator, suggest a timing for some of the compressional event, and give reason to extend the known pre-erosional limit of the Munising Formation in upper Michigan.

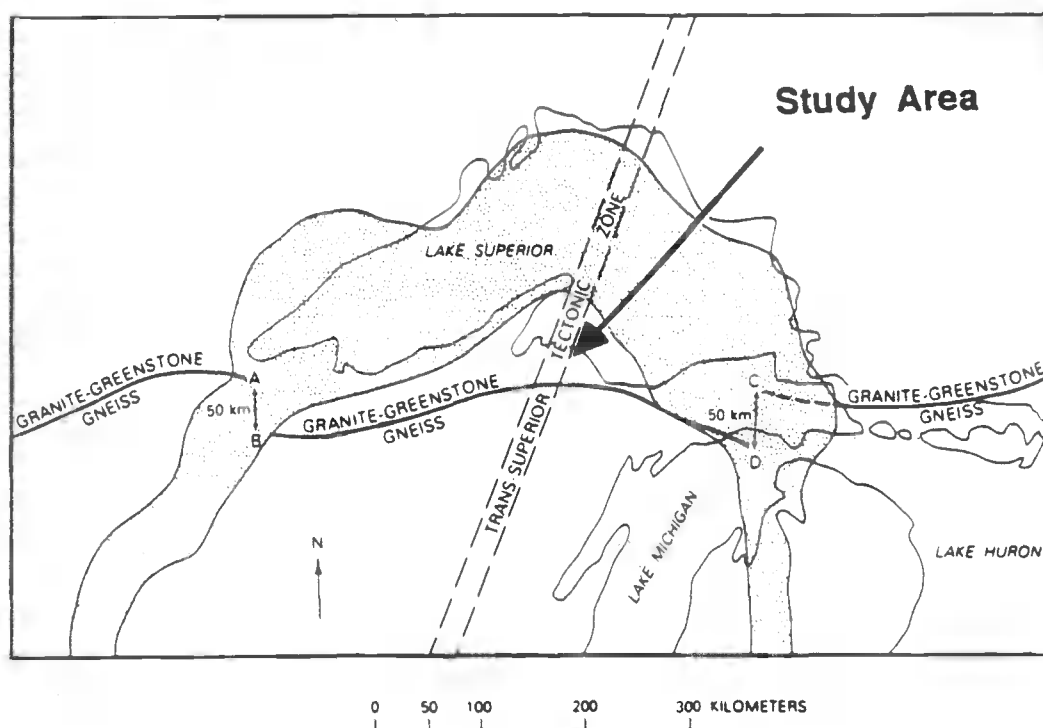


Fig. 1 - Location map and orientation of the Trans-Superior Tectonic Zone (after Klasner et al, 1982).

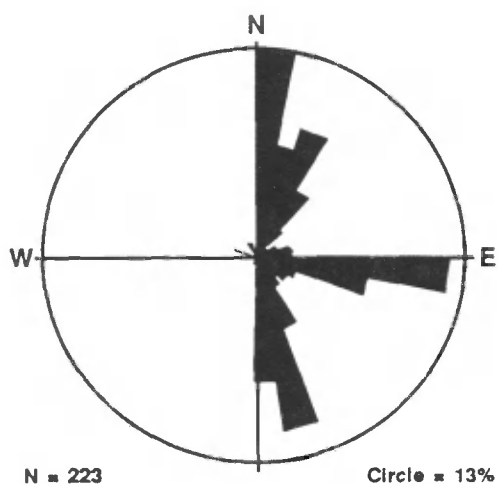


Fig. 2 - Mafic Dike Trends

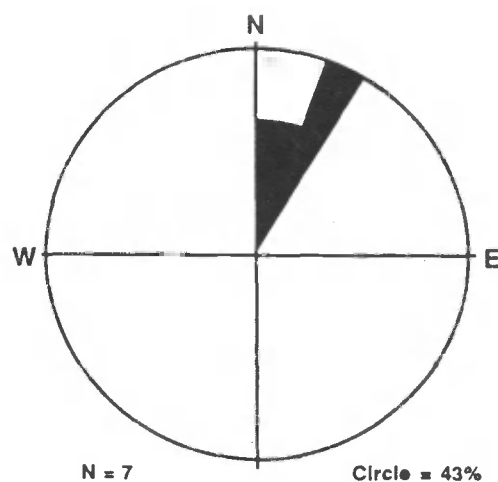


Fig. 3 - Clastic Dike Trends

Research in the Huron Mountains is partially supported by the Geological Society of America, the Michigan Geological Survey, and the University of Wisconsin-Madison.

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