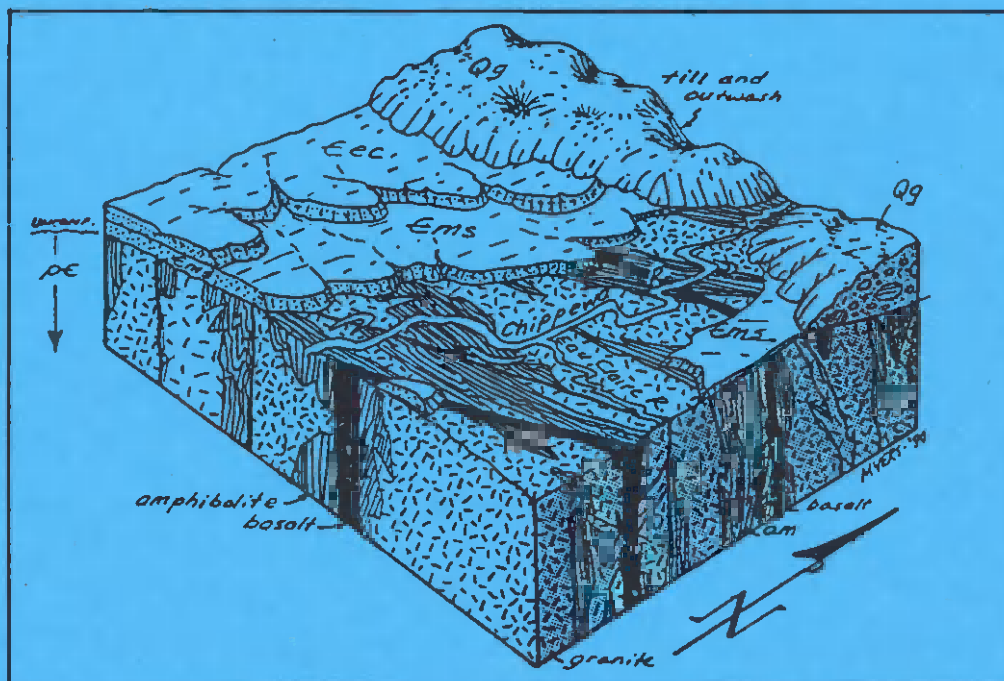




THIRTY-SEVENTH ANNUAL
INSTITUTE ON LAKE SUPERIOR GEOLOGY



PROCEEDINGS: PART 1 - ABSTRACTS

MAY 1-4, 1991
EAU CLAIRE, WISCONSIN

Organization Committee, 37th Annual Meeting ILSG, 1991

General Chairman: Paul E. Myers

PHONE: 715-836-3713

Editor: Lung S. Chan

Geology Department
University of Wisconsin
Eau Claire, WI 54702-4004

PROCEEDINGS VOLUME 37

PART I: ABSTRACTS (Includes Meeting Program)

PART 2: FIELD TRIPS

Reference to material in this volume should follow the example below.

Morey, Glen B., and Southwick, David L., 1991, Manganese mineralization in early Proterozoic iron-formation of the Emily District, Cayuna Range, east-central Minnesota, [abst.]; Institute on Lake Superior Geology Proceedings, 37th Annual Meeting, Eau Claire, WI, 1991; v. 37, part 1, p. 75-76.

Published and Distributed by:
Institute on Lake Superior Geology

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

PURCHASE OF PROCEEDINGS VOLUMES

Copies of the 37th ILSG Proceedings (Part I, Abstracts and Part II, Field Trips) may be purchased during the meeting for \$5.00 (US) each.

Payable to the Institute on Lake Superior Geology

Issues of Proceedings and Abstracts, Part 1, and Field Guidebook, Part 2. from this and previous meetings may be ordered from:

Michael G. Mudrey, Jr.
Address, See above PHONE: 608-263-1705

The cost of each part is \$6.00 U.S. Orders will be filled while supplies last. All volumes back to 1955 are available for photocopying at the prevailing rate from the Michigan Technological University Library through Mr. M.S. Spence, Archivist. Phone 906-487-2505.

37th Annual

Institute on Lake Superior Geology

Proceedings

Ray Wachs Civic Center

Eau Claire, Wisconsin

May 1-4, 1991

Organized by

P.E. Myers, University of Wisconsin-Eau Claire

L.S. Chan, University of Wisconsin-Eau Claire

Volume 37

Part 1 Abstracts

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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
36	1990	Thunder Bay, Ont.
37	1991	Eau Claire, WI

CONSTITUTION OF INSTITUTE ON LAKE SUPERIOR GEOLOGY

Article I

Name

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

Article II

Objectives

The objectives of this organization are:

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

Article III

Status

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

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

Minn. Stat. Anno. 290.01, subd. 4

Minn. Stat. Anno. 290.05(9)

1954 Internal Revenue Code s. 501(c)(3)

Article IV

Membership

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

Article V

Meetings

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

Article VI

Directors

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

Article VII

Officers

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

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

Article VIII

Amendments

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

BY-LAWS

I. Duties of the Officers and Directors

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

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

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

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

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

II. Duties and Expenses

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

III. Rules of Order

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

IV. Amendments

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

Award Guidelines
SAM GOLDICH MEDAL

Preamble

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

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

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

Award Guidelines

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

April 4, 1981

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

STUDENT TRAVEL AWARD

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

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

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

Successful applicants will receive their awards at the time of registration for the Meeting.

BOARD OF DIRECTORS

- 1991 P. E. Myers (with L. S. Chan)
Department of Geology, University of Wisconsin, Eau Claire, Wisconsin
54701
- 1990 M. M. Kehlenbeck
Department of Geology, Lakehead University, Thunder Bay, Ontario P7B 5E1
- 1989 R. W. Ojakangas (with J. C. Green and T. B. Holst)
Department of Geology, University of Minnesota, Duluth, Minnesota 55812
- 1988 J. S. Klasner (with J. D. Hughes and K. J. Schulz)
Department of Geology, Western Illinois University, Macomb, Illinois
61455

Secretary-Treasurer

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

LOCAL COMMITTEE

- | | |
|--------------|--|
| P. E. Myers | General Chairman |
| L. S. Chan | Program and Abstract Editor
and Field Trip Guidebook Editor |
| R. P. Willis | Registration Coordinator |

STUDENT PAPER AWARD COMMITTEE 1991

- | | |
|-------------------------|---|
| J. S. Klasner, Chairman | Western Illinois University, Macomb, Illinois |
|-------------------------|---|

GOLDICH MEDAL COMMITTEE 1990-91

- | | |
|-------------------|--|
| M. G. Mudrey, Jr. | Wisconsin Geologic and Natural History Survey,
Madison, WI |
| F. W. Cambray | Dept. of Geological Sciences, Michigan State
University, East Lansing, MI |
| H. H. Halls | Dept. of Geology, Erindall College, Mississauga,
Ont. L5L 1C0 |

**Biographical Sketch of
WILLIAM J. HINZE
1991 Goldich Medal Recipient**

William J. Hinze began his earth-science career at the University of Wisconsin, where in 1951 he received a bachelor of science in geology. From 1954 to 1955 he served in the U.S. Army Corps of Engineers at their Research and Development Laboratory, after which he returned to the University of Wisconsin, receiving his doctorate in geology and physics in 1957. From 1956 to 1958 he worked as a staff geophysicist for Jones & Laughlin Steel Company. In 1958 he joined the faculty of the department of geology at Michigan State University, where he held appointments of assistant to full professor. In 1972 he took his present post as professor of geophysics in the Department of Earth and Atmospheric Sciences at Purdue University. In 1985 he served as a visiting professor at the University of Lausanne in Switzerland.

In the course of his career Hinze has made many significant and lasting contributions to potential-field geophysics. In addition to numerous abstracts and technical reports, he averages several formal papers per year, either as chief author or as co-author—a truly remarkable record if his formidable professional duties are considered. For instance, from 1975 to 1982 he was chairman of the U.S. National Magnetic Anomaly Map Committee, and from 1985 to 1989 he co-chaired the North American Magnetic Anomaly Map Committee. He edited *The Utility of Regional Gravity and Magnetic Anomaly Maps*, which was published by the Society of Exploration Geophysicists in 1985. From 1986 to 1988 he co-chaired the U.S. National Science Foundation's joint U.S./Indian workshop "Regional Geophysical Lineaments: Their Tectonic and Economic Significance" and co-edited the workshop volume, which was published by the Geological Society of India in 1989. Since 1985 he has dealt with problems concerning the distribution and archiving of geophysical data for the worldwide scientific community and, related to this task, has served in various posts with the U.S. Geodynamics Committee, the International Lithospheric Commission, and the National Academy of Science/National Research Council. From 1988 to the present he has served as a consultant to and member of the Advisory Committee on Nuclear Waste of the Nuclear Regulatory Commission. He has served from 1986 both as a member and vice-chairman of the board of directors of Deep Observation and Sampling of the Earth's Continental Crust, Inc. (DOSECC), and as a co-chairman of the Potential Fields Committee of the Great Lakes International Program on Crustal Evolution (GLIMPCE). He has been a member of the U.S. Geodynamics Committee of the National Academy of Science/National Research Council since 1989.

During his long and successful career Hinze has been at the forefront of geophysical research in the Lake Superior region and the surrounding Midcontinent. His doctoral research, a gravity investigation of the Baraboo Syncline region, which was published in the *Journal of Geology* in 1959, was one of the most innovative gravity studies of its time. His 1960 *Economic Geology* paper on the gravity method in iron-ore exploration, which was largely based on his experiences with Jones & Laughlin Steel Company, became a classic work among explorationists; a slightly revised version reappeared in 1966 in the Society of Exploration Geophysicists' volumes on mining geophysics. During the 1960s Hinze was the principal investigator of several major aeromagnetic and gravity studies of the western Great Lakes, the Upper Peninsula of Michigan, and the Michigan Basin. The aeromagnetic studies over Lake Superior complemented the seismic investigations of

the Lake Superior Experiment, and in 1966 the results were published with the seismic studies in the frequently cited *The Earth Beneath the Continents* (American Geophysical Union Geophysical Monograph 10). In 1982 R.J. Wold and he co-edited *Geology and Tectonics of the Lake Superior Basin* (Geological Society of America Memoir 156), which remains today the definitive reference on Lake Superior geology and geophysics. In recognition of his contributions to Midcontinent geology, he was awarded an honorary membership in the Michigan Basin Geological Society in 1986.

Today Hinze maintains his high profile in geophysical studies of the Lake Superior region. Since the mid-1970s he has been a leading investigator of Midcontinent seismicity and its probable relationship to basement structure. Through his involvement with DOSECC and other agencies, he has been a leading proponent of deep scientific drilling in the Lake Superior region. He and his students are presently conducting combined studies of seismic-reflection, gravity, and magnetic data to investigate crustal structure beneath Lake Superior, a task that epitomizes the strong generalist approach that characterizes his career.

Perhaps Bill Hinze's greatest legacy is his students. Through organizational skills that are unsurpassed and an enthusiasm for his work that is contagious, he has inspired many to learn and achieve far beyond what they thought they were capable. The careers of many successful geophysicists worldwide proudly bear his imprint.

His is truly a career that has made a difference.

VAL W. CHANDLER

Minnesota Geological Survey

Banquet Speaker

Paul K. Sims, U.S. Geological Survey, Denver, Colorado, will be the speaker at the Annual ILSG Banquet in Ray Wachs Civic Center (Rm A) at 8:30 pm on Thursday, May 2, 1991. His topic will be "Archean and Early Proterozoic Geology of the Lake Superior Region -- An Overview." He will be introduced by Glen Morey of the Minnesota Geological Survey.

Acknowledgements

We greatly appreciate the enthusiastic and vital assistance of the many UW-Eau Claire geology student drivers, registration helpers, projectionists, and gofers. We also thank those who volunteered to serve as session chairs, speakers, and authors; their dedication to the philosophy of the ILSG is conspicuous.

36th ANNUAL INSTITUTE ON LAKE SUPERIOR GEOLOGY Thunder Bay, Ontario 1990

The 36th annual meeting of the Institute on Lake Superior Geology was held from May 9 through May 12 in Thunder Bay, Ontario. The meeting was hosted by Lakehead University, Thunder Bay. Manfred M. Kehlenbeck served as General Chairman, Graham Borradaile edited the Field Trip Guidebook, and Philip W. Fralick assisted with the program organization.

The technical sessions and banquet were held at the Airline Motor Hotel on Thursday, May 10 and Friday, May 11. A total of 191 geologists registered for the meeting. Thirty-five oral and twenty poster papers were presented on a wide variety of subjects pertinent to the geology of the Lake Superior Region.

Three of the four field trips were held as both pre- and post- meeting trips on May 9 and May 12 respectively. The fourth field trip was held on May 12. Richard Sutcliffe of the Ontario Geological Survey led 2 trips to the Lac des Illes area to exposures of mafic intrusions, PGE mineralization and granitoid rocks. Graham Borradaile of Lakehead University led 2 field trips to examine the geology of the Shebandowan and Quetico subprovinces. Two trips led by Maurice Lavigue and John Scott of the Ministry of Northern Development and Mines offered insight on base metal mineralization in the Shebandowan greenstone belt. The final field trip was led by Steve Kissin of Lakehead University and focused on granitoid-related mineral deposits in the western Superior region. A total of 187 geologists registered for the seven field excursions. To transport the entire group to relatively isolated areas required a total of 10 vans and 3 large buses. In addition to the trip leaders, the following members of the Geology Department acted as van drivers: P. Fralick, M. Kehlenbeck, S. Kissin, D. Nicol, S. Spivak, B. Seemayer and R. Viitala.

A total of 140 people attended the annual banquet on May 10. Manfred Kehlenbeck presented the 1990 Goldich Medal to Ken Card of the Geological Survey of Canada for his many significant contributions to the geological understanding of the rocks in the Great Lakes Region. J.J. Brummer, M.G. Mudrey and F.W. Cambray served on the Goldich Medal Committee. Dedication of the 1990 I.L.S.G. publication to H.L. James in recognition of his life-time achievements as a geologist in the Lake Superior area was presented by Mike Mudrey. After numerous unsatisfactory replies to inquiring participants during the day-long program, we were delighted to have Herr Doktor Professor Wolfgang Gottlieb von Schlummerklutz (a.k.a. Richard Ojakangas), Direktor of the Wissenschaftliche Institut fuer Welt Probleme entertain all assembled with his presentation of recent research on the origin of Panzerenkotklotzen. His meticulous research and marvellous illustrations made a lasting impression.

Recognition of the importance of student participation in the meetings of the Institute led to the continued financial support of 16 student contributors in 1990. Funds for this assistance which includes waiver of registration fees were drawn equally from the two treasuries of the Institute. A total of \$2,060.00 was spent in 1990. Four awards were

presented for the best oral and poster papers by students for a total of \$600.00. The recipients of the 1990 Best Student Paper Awards were: Stephen D. Geerts, Natural Resources Research Institute, Duluth, MN.; Joseph D. Jablinski, University of Minnesota, Duluth; Steven R. Koehler, University of Wisconsin, River Falls; and David B. Saja, Michigan Technological University, Houghton. J. Klasner, W. Kangas and D. Southwick served on the Best Student Paper Committee.

The I.L.S.G. Board of Directors met on May 4. The meeting was attended by J. Kalliokoski, M. Kehlenbeck, J. Klasner, Lung Chan, M. Lavigne, P. Myers, M. Mudrey, R. Ojakangas, R. Sage, and M. Smyk.

The following items were discussed:

- (1) The site for the 1991 meeting will be at Eau Claire, WI - Paul Myers as General Chairman.
- (2) Voted to accept Henry Halls on the Goldich Medal Committee to replace J.J. Brummer whose term has expired.
- (3) To continue the practice of travel support for students presenting papers. Funds to be drawn equally from the ILSG treasuries in the United States and Canada.
- (4) The treasurer's report by J. Kalliokoski was received. The balance in the General account as of March 27, 1990 was \$8,463.75. The Goldich Medal Fund contained \$911.76. Fourteen Medals are in care of G.B. Morey. Since the 1990 meeting was held in Thunder Bay the account was actively changing. Consequently, no meaningful statement could be made. M. Kehlenbeck, however, assured the Board that all expenses would be met and that no deficits would be incurred.
- (5) Offers to host future meetings of the Institute were received from the Ministry of Northern Development and Mines (Marathon, Ontario), Michigan Technological University, and the Minnesota Geological Survey.
- (6) After many years of service, Joe Kalliokoski tendered his resignation as Secretary-Treasurer of the Institute. Joe has not only been carrying out the duties of this office, but has been very active in many aspects of the functioning of the Institute and has a sustained record of contributions. His sage advice has been a great help and comfort to many general chairmen in the past. Voted to ask Mike Mudrey to assume the office of Secretary-Treasurer.

I wish to thank all those who dedicated their time and expertise to make the 1990 meeting a success.

Respectfully submitted,

CALENDAR OF EVENTS

TUESDAY, APRIL 30

- 3:00-5:00 p.m.** Early Registration for Field Trips #1 and #2 Participants - Civic Center Inn (CCI) Lobby
- FIELD TRIP #1** P.K. Sims, and J.S. Klasner (Leaders) "The Mountain shear zone - a post-Penokean discrete ductile deformation zone"
5:00 p.m. Two vans depart for Antigo (Park Inn)
8:30 p.m., Park Inn, Pre-Field Trip Conference

WEDNESDAY, MAY 1

- FIELD TRIP #1** 8:00 a.m. Vans depart from Park Inn, Antigo, for the mountain area. Vans return to CCI by about 9:00 p.m.
- FIELD TRIP #2** L.S. Chan, P.E. Myers, and R.L. Hay, (Leaders): "Features and significance of the Precambrian-Cambrian contact in western Wisconsin"
8:00 a.m. Pre-trip Seminar CCI, Farwell Rm.
8:20 a.m. Vans depart from CCI Lobby
- 2:00-5:00 p.m.** Pre-Conference Planning Session - Staff, CCI Gibson Room
- 4:00-8:00 p.m.** Registration and check-in for pre-registrants, Civic Center Inn Lobby
- 8:00-11:00 p.m.** Informal Get-together and Cash Bar
Music by: Bill Jordan Jazz Quintet

THURSDAY, MAY 2

- 7:15 a.m** Registration - Lobby, Civic Center Inn (CCI)

TECHNICAL SESSION

All Technical Sessions are in Room C, Ray Wachs Civic Center (RWCC); Poster Sessions in RWCC Rooms D and E. Schedules of oral papers are shown on pages xiii and xiv. Contributors should have posters up by 9:00 a.m.

- 8:00 a.m.** Introduction and Welcome: Paul Myers, Conference Chairman, and Larry Schnack, Chancellor, University of Wisconsin - Eau Claire
- 8:20-10:00 a.m.** Morning Session #1. Chairs: R.W. Ojakangas and A.B. Dickas
- 10:00 a.m.** COFFEE BREAK
- 10:20-11:50 a.m.** Morning Session #2. Chairs: G.L. LaBerge and K. Schultz

- NOON-2:00 p.m. **BOARD LUNCHEON AND ANNUAL MEETING:** *Farwell Room, CCI*
- 12:30-1:30 p.m. **POSTER SESSION #1 - Authors present** (Poster papers, p. xv)
- 1:40-3:00 p.m. **Afternoon Session #1.** *Chairs: V.W. Chandler and G.B. Morey*
- 3:00 p.m. **COFFEE BREAK -- Remove Poster Papers**
- 3:20-4:50 p.m. **Afternoon Session #2.** *Chairs: M.M. Kehlenbeck and C. Craddock*
- 6:00-7:30 p.m. **CASH BAR: RWCC ROOM A**
- 7:30-10:00 p.m. **ANNUAL ILSG BANQUET -- RWCC Rooms A and B**
- Presentation of the Goldich Medal to W.J. Hinze, Purdue University**
by V.W. Chandler
- Speaker: Paul K. Sims, "Archean and Early Proterozoic Geology of the**
Lake Superior Region -- An Overview"; introduced by G.B. Morey.

FRIDAY, MAY 3, 1991

- 8:00 a.m.-3:30 p.m. **Registration and Sale of Extra Proceedings Volumes**
- 8:20 a.m. **Morning Session #1.** *Chairs: M. G. Mudrey, Jr. and T. A. DeMatties*
- 10:00 a.m. **COFFEE BREAK**
- 10:20-11:30 a.m. **Morning Session #2.** *Chairs: G.W. Adams and B.A. Brown*
- 12:30-1:30 p.m. **POSTER SESSION #2 -- Authors present** (poster papers, p. xvi)
- 1:40-2:40 p.m. **Afternoon Session #1.** *Chairs: W.S. Cordua and M. Jirsa*
- 2:40 p.m. **Student Award Presentation, John Klasner**
- 3:00 p.m. **COFFEE BREAK -- Remove Poster Papers**
- 3:20-4:30 p.m. **Afternoon Session #2.** *Chairs: J. Kaliokoski and J. C. Green*
- 7:00-8:30 p.m. **Pre-Trip #3 Seminar, CCI, Farwell Room, M.G. Mudrey, Jr. and B.A. Brown**

SATURDAY, MAY 4, 1991

- FIELD TRIP #3** **M.G. Mudrey, Jr., and B.A. Brown (Leaders), "Proterozoic**
volcanogenic massive sulfide deposits of northwestern Wisconsin"
8:00 a.m. Bus departs from front entrance of CCI

PROGRAM - DAY 1, THURSDAY, MAY 2, 1991

Time	Authors	Title
8:20 AM	*Allen, David J. and William J. Hinze	The Wisconsin Gravity Minimum: Source & Implications
8:40 AM	*Allen, David J., William J. Hinze, and William F. Cannon	The Relationship of Topography and Gravity over the Lake Superior Swell: Evidence for a Keweenaw Hot Spot
9:00 AM	Chandler, Val W.	Aeromagnetic Surveying Program in Minnesota: Past and Future Perspectives
9:20 AM	Osterberg, Steven A. and Ian R. Morrison	Physical Volcanology of the Footwall Rocks at the Winston Lake Massive Sulfide Deposit
9:40 AM	Dickas, Albert B. and M.G. Mudrey, Jr.	Geology & Petrography of the Amnicon Pluton, Douglas County, Wisconsin
10:00 AM		COFFEE BREAK
10:20 AM	Read, William F.	The Neda Iron Formation -- A Product of Vulcanism?
10:40 AM	Anderson, Raymond R.	The Amoco M.G. Eischeid Oil Test: 4200 Meters of Clastic Rocks of Midcontinent Rift System
11:00 AM	Morey, G.B. and D.L. Southwick	Manganese Mineralization in Early Proterozoic Iron-Formation of the Emily District, Cuyuna Range, East-Central Minnesota
11:20 AM	Bachman, R.L.	The Homestake Mine: An Early Proterozoic Iron-Formation Hosted Gold Deposit
11:40 AM		CONCLUDING REMARKS BY SESSION CHAIRS
11:50 AM		END OF MORNING SESSION
12:30 PM		POSTER SESSION
1:40 PM	Laberge, Gene L.	Early Proterozoic Rocks in the Monico, Wisconsin Area: Implications on the Wisconsin Magmatic Terrane
2:00 PM	Hemming, S., G.N. Hanson, S.M. McLennan, and W.D. Sharp	Isoclinal Slump Folds in the Lower Pokegama Quartzite: Evidence for Seismicity and Slope Instability During Deposition of the Animikie Group
2:20 PM	*Craddock, John P. and Andrew Moshoian	Continuous Strike-Slip Fault-En Echelon Fracture Arrays in Deformed Archean Rocks: Implications for Fault Propagation Mechanics
2:40 PM	*Jerde, Eric A.	Magmatic Evolution in the Midcontinent Rift: Evidence from Hypabyssal Rocks of the North Shore of Lake Superior
3:00 PM		COFFEE BREAK
3:20 PM	Cambray, F. William and Kazuya Fujita	Collision Induced Ripoffs, Ancient and Modern: The Midcontinent Rift System and the Red Sea-Gulf of Aden Compared
3:40 PM	Cambray, F. William and Glenn Scott	A Late Keweenawan Thrust ? Marquette County, Michigan
4:00 PM	*Manson, M.L. and H.C. Halls	The Geology and Geophysics of Major Post-Keweenawan Faults in the Eastern Lake Superior Region
4:20 PM	Cambray, F. William and Joseph J. Mancuso	Detachment Faulting and the Origin of the Asymmetric Depositional Pattern of the Marquette Trough
4:40 PM		CONCLUDING REMARKS BY SESSION CHAIRS
4:50 AM		END OF AFTERNOON SESSION

PROGRAM - DAY 2, FRIDAY, MAY 3, 1991

Time	Authors	Title
A.M.: SYMPOSIUM ON MINERAL RESOURCES POTENTIAL OF NORTHERN WISCONSIN		
8:20 AM	DeMatties, T.A. and M.G. Mudrey, Jr.	Geological Setting of the Early Proterozoic Base- and Precious Metal-Rich Metavolcanic Belt of Wisconsin
8:40 AM	DeMatties, T.A. and W.F. Rowell	Bend, A Lower Proterozoic, Copper- and Gold-Enriched Volcanogenic Massive-Sulfide Deposit in Taylor County, Wisconsin
9:00 AM	Hanson, Jay C.	Ground Geophysical Surveys Leading to the Bend Copper-Gold Discovery
9:20 AM	Kennedy, Lawrence P., Teresa A. Harding, John A. Schaff, and Anne M. Zielinski	The Lynne Massive Sulfide Deposit, Oneida County, Wisconsin
9:40 AM	Thresher, Jr., J.	Geology and Mineralogy of the Flambeau Deposit, Oneida County, Wisconsin
10:00 AM		COFFEE BREAK
10:20 AM	Mudrey, Jr., M.G. and B.A. Brown	Platinum Group Element Potential of Keweenawan Intrusive Rock in Wisconsin
10:40 AM	Brown, Bruce, A.	Nonmetallic Mineral Resources and Minor Metals Potential of Northern Wisconsin
11:00 AM	Evans, Thomas J.	Regulating Metallic Mineral Development in Wisconsin
11:20 AM		CONCLUDING REMARKS BY SESSION CHAIRS
11:30 AM		END OF MORNING SESSION
12:30 PM		POSTER SESSION
1:40 PM	Klasner, John S. and P.K. Sims	Thick-Skinned Backthrusting in the Felch-Calumet Troughs Region, Northern Michigan -- A comparison with the Southern Alps
2:00 PM	Middleton, Michael D.	A Preliminary Study of Rejuvenated Movement Along a Precambrian Fault, St. Croix County, Wisconsin
2:20 PM	Miller, J.D., Jr., J.B. Paces, and R.E. Zartman	Geochronology of the Duluth Complex: A Progress Report
2:40 PM		STUDENT AWARD PRESENTATION
3:00 PM		COFFEE BREAK
3:20 PM	Seifert, Karl E., Zell E. Peterman, and Scott E. Thieben	The Nature and Source of Midcontinent Rift Igneous Rocks
3:40 PM	Windom, Kenneth E., W.R. Van Schmus, Karl E. Seifert, E.T. Wallin, and R.R. Anderson	Archean and Proterozoic Tectono-Magmatic Activity Along the Southern Margin of the Superior Province in Northwestern Iowa, USA
4:00 PM	Chan, Lung S.	Paleomagnetism of Central Wisconsin Dike Swarm: Constraints on Thermomechanical Model of Midcontinent Rift
4:20 PM		CONCLUDING REMARKS BY SESSION CHAIRS
4:30 PM		END OF AFTERNOON SESSION

*Student Contribution

POSTER SESSION

**DAY 1, THURSDAY, MAY 2, 1991,
12:30 PM - 1:30 PM, ROOMS D & E, RW CIVIC CENTER**

*Brehm, Daniel J., C. Patrick Ervin, M.G. Mudrey, Jr., B.A. Brown, & M.L. Czechanski	Extension of Gravity Filed Coverage in East-Central Wisconsin: 1990 COGEOMAP Program
Brown, B.A. and R.S. Maass	Preliminary Bedrock Geology Map of Eau Claire County, Wisconsin
*Dahl, Linda J. and Susan E. Brink	Preliminary Drill Core Study of Two Holes Drilled on the Cuyuna Iron Range and Emily Manganiferous Iron Formation District of Minnesota
*Mariano, J. and W.J. Hinze	Geophysical Investigations of the Midcontinent Rift in Eastern Lake Superior Using Variable Magnetization Modeling
Nicholson, S.W., K.J. Schulz, W.F. Cannon, and L.G. Woodruff	The Porcupine Mountains Area, Michigan - a Keweenawan Central Volcano?
Reichhoff, J.A., S.A. Hauck, and D.L. Southwick	Lithogeochemistry and Geological Mapping in the Vermilion Greenstone Belt, Minnesota, as an Aid to Mineral Exploration
Severson, Mark J. and Steven A. Hauck	Correlation of Igneous Units at the Minnamax Deposit, NE Minnesota
Teskey, D.	Three-Dimensional Modelling of the Magnetic Anomaly - Central Lake Superior
Turnock, A.C., D.C. Kamineni, and R. McGregor	Chemistry and Metamorphism of an Archean Pillow Basalt
Welsh, James L. and Jayne Reichhoff	Geochemistry of Archean Rocks from the Virginia Horn area: Preliminary Interpretations
*Witthuhn, Kathleen	Stress Analysis of the Midcontinent Rift in Michigan and Minnesota
Zanko, L., A. Gokee, B. Dewey, S. Hauck, and J. Pastor	Geostatistical and GIS Evaluation of Biochemical and Ecological Data From Three Mineralized Sites (Au & Cu-Ni-PGE), Northeastern Minnesota: Implications for Mineral Exploration in a Boreal Forest

*Student Contribution

POSTER SESSION

DAY 2, FRIDAY, MAY 3, 1991
12:30 PM-1:30 PM, ROOMS D & E, RW CIVIC CENTER

Campbell, Frederick K.	The Feasibility of Recovering Metals From a Hazardous Waste Site; A Brief Case Study
Geerts, Stephen D.	Geology of Platinum Group Element-Enriched Horizons within the Dunka Road Copper-Nickel Prospect, St. Louis County, Minnesota
Green, John C., Ed. Venzke, and Tom Lawler	Drift Pebble Lithology of the Tomahawk Road Area, Lake County, Minnesota, Used to Help Infer Local Bedrock
Heine, John J., Tom A. Toth, Steven A. Hauck, and George W. Shurr	Geology of the Meridian Aggregates Quarry and the Surrounding Area, St. Cloud, Minnesota: A Study of the Bedrock Influences on the Pre-Late Cretaceous Weathering Profile
Hinz, Peter	Industrial Minerals of Northwestern Ontario
Hinz, Peter	Exploration and Mining Activity in Northwestern Ontario
*Johnson, James S., Denise A. Stavish, Mary K. Tozer, and George W. Schurr	Surface Expression of Major Bedrock Structural Features
Morrison, Ian R.	Pick Lake Zinc-Copper-Silver Deposit
*Thompson, M.D., L.D. McGinnis, M.G. Mudrey, Jr., and C.P. Ervin	Midcontinent Rift Structure Interpreted From the GNI/Argonne Seismic Data Set
Toth, Thomas A., John J. Heine, & Steven A. Hauck	Regional Stratigraphic Model of Late Cretaceous Sediments and their Relationship with the Underlying Pre-Late Cretaceous Weathering Profile along the Minnesota River Valley, Minnesota
Woodzick, Thomas L., Gary P. Murdock, and Douglas E. Pride	A Study of Thematic Mapper Lineaments in Northwest Nevada

*Student Contribution

ABSTRACTS

The Wisconsin Gravity Minimum: Source and Implications

David J. Allen and William J. Hinze, Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, Indiana

The Wisconsin Gravity Minimum (Fig. 1) attains its most negative values of approximately -95 milliGals over the outcrop of the 1.5 Ga Wolf River Batholith, but extends discordantly across the Archean Marshfield Terrane, the 1.9-1.8 Ga Penokean Pembine-Wausau Terrane, and the 1.76 Ga anorogenic rhyolite-epizonal granite terrane of southern Wisconsin.

The edges of the minimum are characterized by sharp gradients indicating that the source of the anomaly lies at shallow depths. The north-northeast trend of the anomaly is discordant with the east-west Penokean structural grain in Wisconsin, suggesting that the source of the anomaly may be younger than 1.8 Ga. Thus, we propose that the entire Wisconsin Gravity Minimum is produced by the Wolf River Batholith. Although the batholith outcrops only in northeast Wisconsin, the anomaly suggests that it lies buried beneath a thin cover of older Precambrian roof rocks and early Paleozoic sedimentary rocks throughout a substantial portion of Wisconsin.

Forward modeling of gravity data along several profiles across the Wisconsin Gravity Minimum supports the buried Wolf River Batholith hypothesis. South and west of the its outcrop, the Wolf River Batholith may be buried beneath approximately 4 km of older Precambrian rock, and the batholith extends to depths between 10 and 15 km (Allen, 1990). Figure 2 is an interpreted geologic cross-section based on a gravity model along a northwest-southeast profile (Fig. 1). In northern Wisconsin, the negative gravity anomaly is produced by the density contrast between the granitic rocks of the Wolf River Batholith and the denser Penokean and Archean rocks. In southern Wisconsin, however, the 1.76 Ga anorogenic rhyolites-epizonal granites and Baraboo quartzites have densities similar to that of the Wolf River Batholith; thus, the source of the gravity anomaly in southern Wisconsin is the density contrast between the Wolf River Batholith and the denser, pre-1.76 Ga rocks which underlie the anorogenic granites, rhyolites, and quartzites. The lower crustal structure shown in Figure 2 was obtained by projecting a crustal model based on a combined seismic reflection-gravity interpretation along GLIMPCE line H in Lake Michigan (Cannon et al., 1991) west along geophysical-anomaly strike into Wisconsin. As shown in Figure 2, the lower crustal structure does not significantly contribute to the Wisconsin Gravity Minimum.

The emplacement of the Wolf River Batholith may have been controlled by pre-existing structures. For example, the Eau Claire Shear Zone, a 1.8 Ga suture between the Pembine-Wausau Terrane and the Marshfield Terrane, has been identified beneath Lake Michigan (Cannon et al., 1991) and projects through the most negative portion of the Wisconsin Gravity Minimum where the Wolf River Batholith is thickest (Fig. 2). The shear zone may have acted as a conduit along which magma was preferentially transported at 1.5 Ga. Also, the Wolf River Batholith outcrops north of the shear zone, but is buried to the south. The northern portion of the batholith may have been uplifted relative to the southern portion at a later time during shear zone reactivation. Alternatively, the batholith originally may have been emplaced to shallower levels in the Pembine-Wausau Terrane than in the Marshfield Terrane.

The southeast margin of the Wisconsin Gravity Minimum closely approximates a

prominent magnetic boundary which separates a positive anomaly to the northwest from a negative anomaly to the southeast (Fig. 2). This magnetic boundary, herein called the Winnebago magnetic anomaly, continues northeast beyond the Wisconsin Gravity Minimum, suggesting that it is not the magnetic signature of the edge of the batholith, but instead reflects a pre-1.5 Ga structure which controlled the location of the southeast margin of the Wolf River Batholith.

The general correlation of the Wisconsin Gravity Minimum with the Wisconsin Arch suggests a possible genetic relationship. Since the Wolf River Batholith is less dense than the surrounding rocks, it may have been intermittently uplifted over the past 1.5 Ga in response to buoyancy forces.

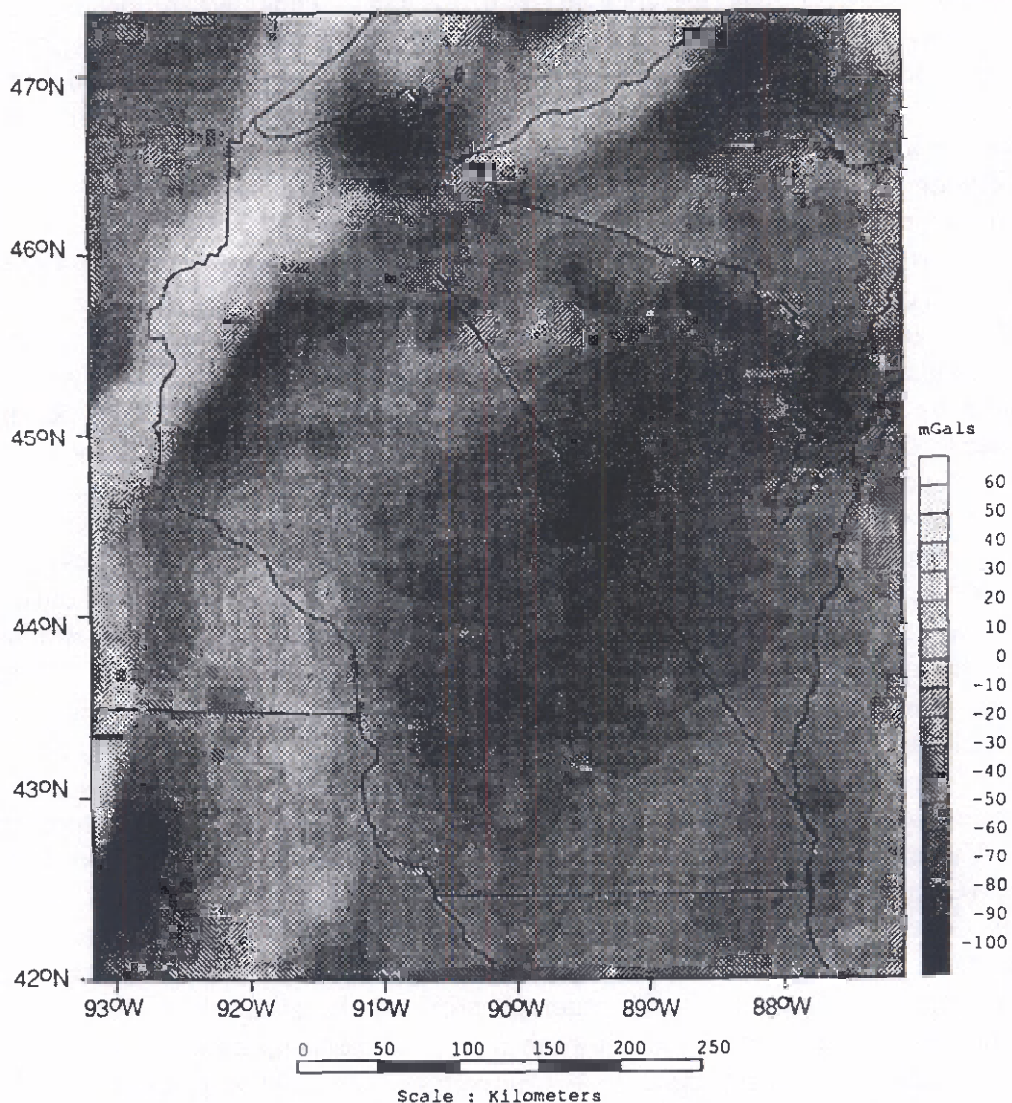


Figure 1: Bouguer gravity anomaly map of the Wisconsin area based on four kilometer gridded data. The line indicates the profile shown in Figure 2.

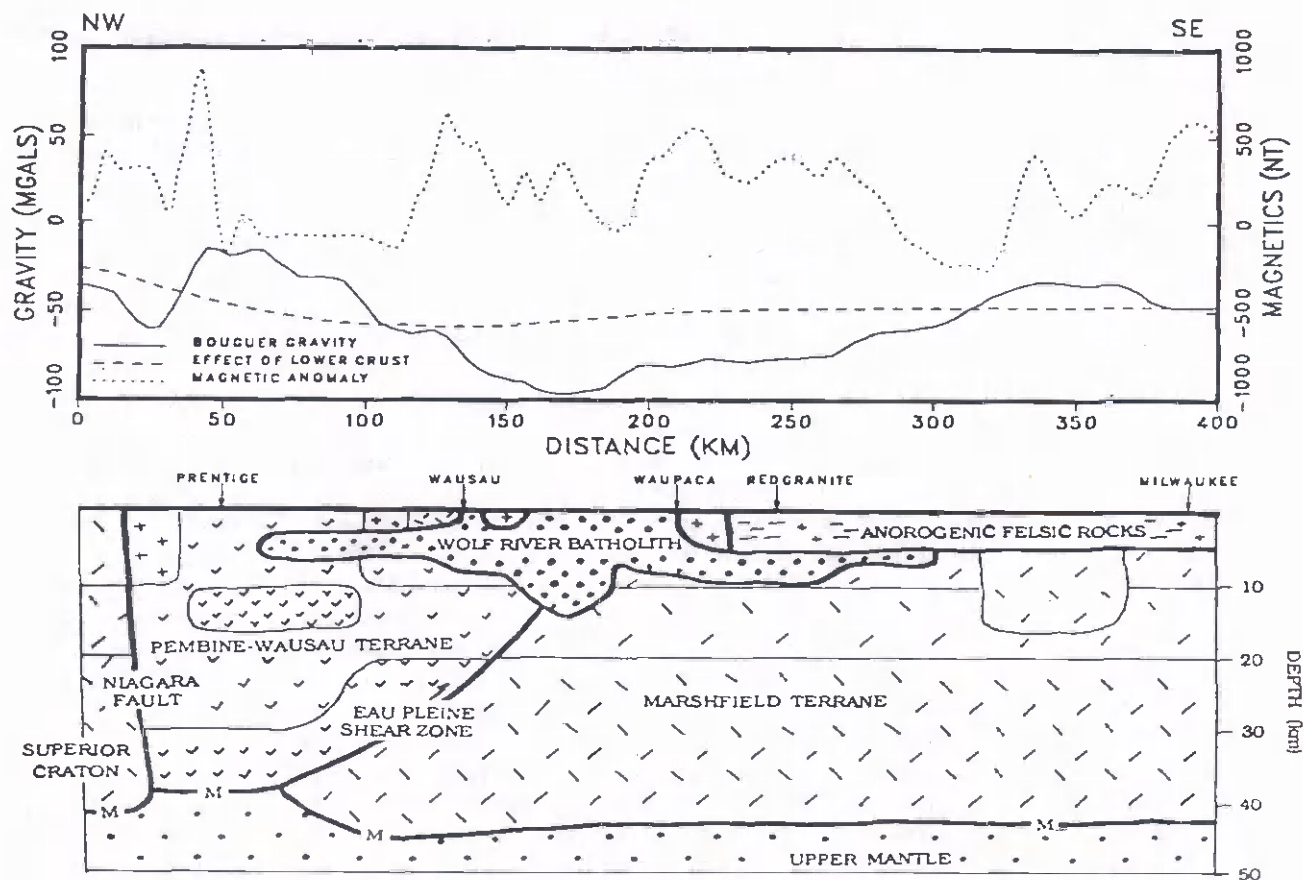


Figure 2: Bouguer gravity and total intensity magnetic anomaly profiles and related geologic model showing major crustal units and terranes. The dashed line indicates the gravitational effect of density variations beneath 20 km. See Figure 1 for the location of the profile.

REFERENCES CITED

- Allen, D. J., 1990, The Wisconsin gravity minimum: source and implications, unpub. M. S. Thesis, Purdue Univ., W. Lafayette, IN, 183 p.
- Cannon, W. F., Lee, M. W., Hinze, W. J., Schulz, K. J., and Green, A. G., 1991, Deep crustal structure of the Precambrian basement beneath northern Lake Michigan, midcontinent North America: *Geology* 19, 207-210.

The Relationship of Topography and Gravity over the Lake Superior Swell: Evidence for a Keweenaw Hot Spot?

David J. Allen, William J. Hinze, Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, IN, and William F. Cannon, USGS, Reston, VA

The Lake Superior Swell (Dutch, 1981) is a broad topographic dome surrounding the Lake Superior Basin, the location of the most intense 1.1 Ga Keweenawan rifting activity. Centered on Lake Superior is a radial drainage pattern of approximately 1000 km diameter. Within this area, streams flow radially outward from the relatively small inward-directed drainage system of the Lake Superior Basin (Figure 1). In addition, recent analysis of the regional gravity and topographic data indicates that a broad negative gravity anomaly is also centered on Lake Superior and is related to isostatic compensation of the Lake Superior Swell.

The regional negative anomaly is defined by determining average gravity as a function of radial distance from a central point in Lake Superior (Figure 1). As shown in Figure 2, the average gravity decreases, in an approximately linear manner, from a radial distance of 650 km to 300 km. Within 300 km, the gravity anomalies produced by the Midcontinent Rift obscure the regional anomaly, while beyond 650 km, the average gravity is influenced by remote features unrelated to the Lake Superior Swell. Analysis of topographic data indicates that the average topography varies in an inverse manner to the gravity (Figure 2). Furthermore, the relationship between average gravity and average topography (Figure 3) suggests that the Lake Superior Swell is in approximate isostatic equilibrium (for a fully compensated topographic load of density 2.67 g/cm^3 , slope = -112 mGals/km).

Recently, it has been proposed that a mantle plume (the Keweenaw hot spot) is related to the origin of the 1.1 Ga rifting and igneous event which led to the large volume of basalts and the short time span of their eruption (Hutchinson et al., 1990; Nicholson and Shirey, 1990). We propose that the drainage pattern, the topographic dome, and the negative gravity anomaly may still reflect the short-lived Keweenaw hot spot.

The persistence of the topographic dome must be isostatically related to a fundamental change imprinted on the lithosphere by the mantle plume. For example, the Lake Superior Swell may be supported isostatically by a crust which has been thickened by the addition of Keweenawan basaltic rocks. Beneath the Lake Superior Basin, for example, the crust thickens by as much as 15 km. The negative gravity anomaly, however, extends well beyond the Lake Superior Basin, suggesting that the crust may have been thickened (to a lesser degree) over a much broader area, well beyond the outcrop of the rift rocks. The observed gravity anomaly may be accounted for by a gradual thickening of the crust (of approximate magnitude 1 km) from 650 km to 300 km radial distance (Allen, 1990).

The source of the gravity anomaly, alternatively, may be a density contrast in the mantle related to the extraction of the Keweenawan basalts. The depleted upper mantle rocks are expected to be less dense (by at most 0.10 g/cm^3) than undepleted rocks due to the removal of the dense phase garnet and/or an increase in the MgO/FeO ratio (Boyd and McCallister, 1976; Oxburgh and Parmentier, 1977). The

negative gravity anomaly may be accounted for by an upper mantle which becomes increasingly depleted toward the center of the Lake Superior Swell. Again, this suggests that the upper mantle was disturbed over a region much broader than the outcrop of the rift rocks.

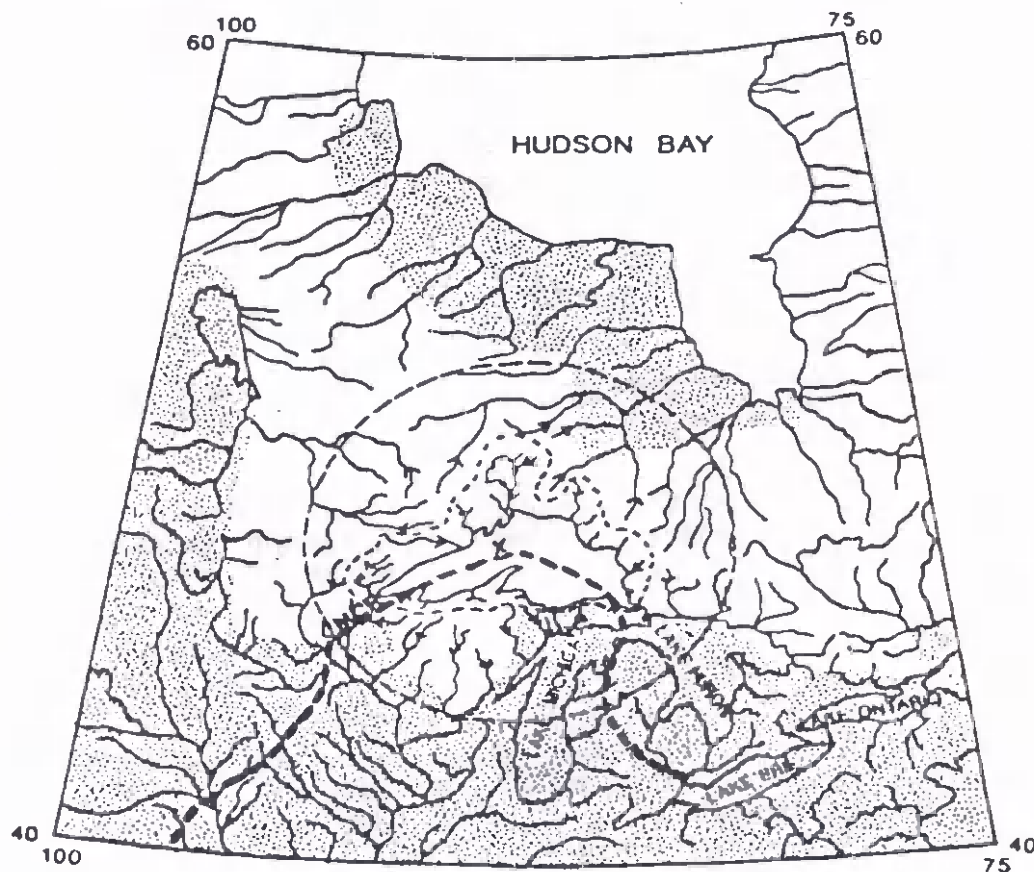


Figure 1: Map of part of central North America showing major drainage systems. Arrows denote direction of stream flow. Shaded areas are covered by Phanerozoic platform sedimentary rocks; unshaded areas are exposed Precambrian rocks of the Canadian Shield. Heavy dashed line shows approximate axis of the Midcontinent Rift (MCR). Short dashed line is outline of present Lake Superior drainage basin. Circle is 1000 km diameter. Cross in Lake Superior indicates position of central point used in the radial averaging analysis.

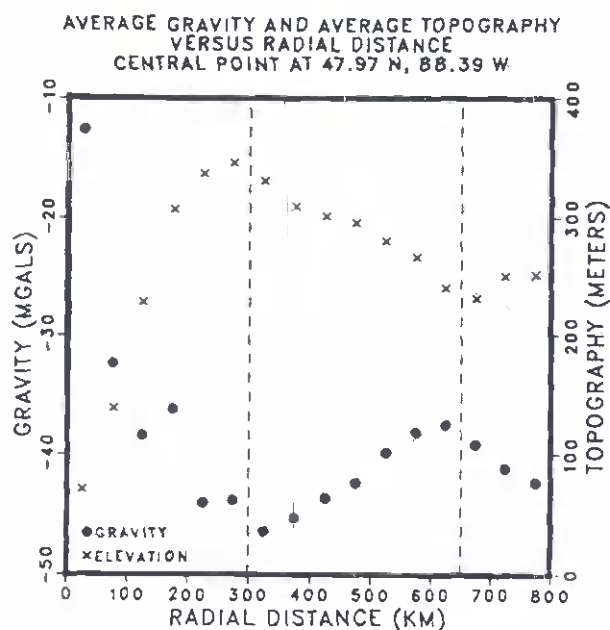


Figure 2: Average gravity and average topography vs. radial distance from the central point indicated in Figure 1.

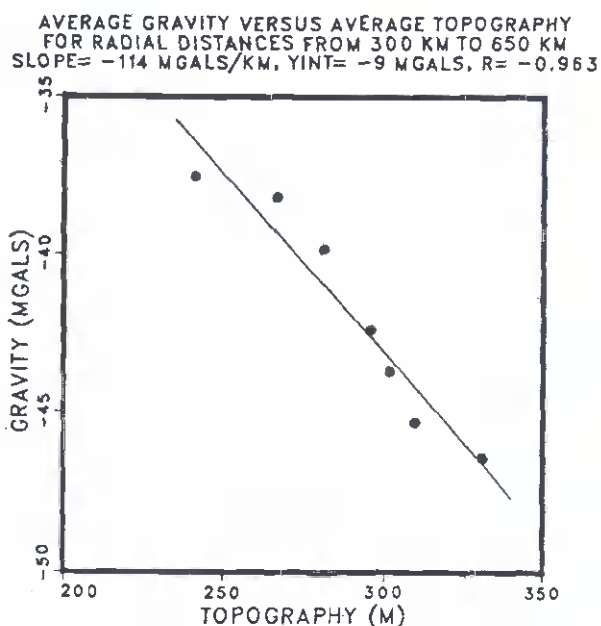


Figure 3: Average gravity vs. average topography for radial distance between 300 km and 650 km.

REFERENCES CITED

- Allen, D. J., 1990, The Wisconsin gravity minimum: source and implications, unpub. M. S. Thesis, Purdue Univ., W. Lafayette, IN, 183 p.
- Boyd, F. R., and McCallister, R. H., 1976, Densities of fertile and sterile garnet peridotites: *Geophys. Res. Lett.* 3, 509-512.
- Dutch, S. I., 1981, Isostasy, epeirogeny, and the highland rim of Lake Superior: *Z. Geomorph. N. F., Suppl.-Bd.* 40, 27-41.
- Hutchinson, D. R., White, R. S., Cannon, W. F., and Schulz, K. J., 1990, Keweenaw hot spot: geophysical evidence for a 1.1 Ga mantle plume beneath the Midcontinent Rift System: *J. Geophys. Res.* 95(7), 10869-10884.
- Nicholson, S. W., and Shirey, S. B., 1990, Midcontinent Rift volcanism in the Lake Superior region: Sr, Nd, and Pb isotopic evidence for a mantle plume origin: *J. Geophys. Res.* 95(7), 10851-10868.
- Oxburgh, E. R., and Parmentier, E. M., 1977, Compositional and density stratification in oceanic lithosphere - causes and consequences: *J. Geol. Soc. London* 133, 343-355.

THE AMOCO M.G. EISCHEID OIL TEST: 4200 METERS OF CLASTIC ROCKS OF MIDCONTINENT RIFT SYSTEM

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The M.G. Eischeid #1 deep petroleum test well was drilled by Amoco Production Company between April and October, 1987, near the town of Halbur (Carroll County) in west-central Iowa. The well reached a total depth of 5355 m (17,851 feet) including 235 feet of glacial drift, 130 feet of Cretaceous Dakota Formation, 2392 feet of Paleozoic strata including Pennsylvanian through Cambrian units dominated by carbonates, 813 feet of an unidentified sandstone unit ("Unit H"), and 14,085 feet of "Red Clastics" assigned to the Keweenawan Supergroup, before reaching t.d. 151 feet into a mafic dike in the crystalline basement. The well was primarily drilled by rock bit, with duplicate samples sets presently repositied at the geological surveys of Iowa and Nebraska. In addition to the cuttings, five short cores were taken (see Fig. 1 for intervals cored) totaling about 66 feet. Splits are repositied at the Iowa Geological Survey Bureau.

A series of preliminary investigations of Eischeid rock samples and geophysical logs were conducted shortly after the release of the materials. These investigations included stratigraphic and petrographic studies, analysis of source rock potential, porosity studies, clay mineralogy analysis, fluid inclusion studies, integrated isotopic and fluid inclusion analysis of vein-filling minerals, and the determination of an age for the basal dike. The results of these studies were published by the Iowa Geological Survey Bureau (Anderson, 1990a).

Of particular interest in the Eischeid well were the 14,000 feet of Keweenawan "Red Clastic" strata, one of the thickest clastic sections in the Midcontinent Rift system (MRS) strata ever examined. The six formations initially described and assigned to the Keweenawan Supergroup by Witzke (1990) constitute two groups temporarily named the "Upper" and "Lower Red Clastic Sequences" (Figure 1).

Unit H

"Unit H" displays a coarser average grain size and is less well-cemented than the rocks of underlying "Upper Red Clastic Sequence", and is more arkosic than the quartz arenites of the overlying Mt. Simon Fm. The unit was discussed by McKay (1990) who described it as being dominated by two primary lithologies, a fine to very coarse arkosic sandstone and a micaceous, shaley to sandy siltstone. McKay reported trace amounts of microbrecciated lithic fragments in "Unit H", similar to fragments observed in all units of the "Red Clastic Sequences", and interpreted the fragments as the products of structural movements along fault zones that pervasively cut the MRS sequence. Grains with similar lithologic fabrics are not observed in the Mt. Simon interval of the well and have not been reported in similar age rocks in the region. Consequently these rocks are thought to be of Proterozoic age and the may be associated with the "Upper Red Clastic Sequence".

"Upper Red Clastic Sequence"

The "Upper Red Clastic Sequence" is composed of three informal units totalling 6895 feet, and occupies the same stratigraphic position as the Bayfield Group of Wisconsin with which it is correlated. Both groups are dominated by fluvial deposition, but display different compositional characteristics. The Bayfield is more mature than the underlying Oronto Group, whereas Ludvigson and others (1990) reported that the "Upper Red Clastic Sequence" is less mature than its underlying "Lower Red Clastic Sequence". An upward increase in the volcanic rock fragment component of "Upper Red

Clastic Sequence" sandstones may record the unroofing of basalts on the nearby central horst (Anderson, 1990b).

"Lower Red Clastic Sequence"

The "Lower Red Clastic Sequence" is also composed of three informal units and totals 7190 feet of strata. It is the basal clastic sequence in the Eischeid well and bears many similarities to the Oronto Group of Wisconsin with which it is correlated. The primary difference between the two groups are the basal units: the Copper Harbor Conglomerate (Oronto Gp) being dominated by very coarse volcanic clasts, "Unit B" ("Lower Red Clastic Sequence") being dominated by quartz sand grains. These differences can be explained by the relative positions of the Oronto Gp and the Eischeid well in the MRS. The Oronto Group is described from exposures on the central horst. Early in rift history the horst area was a graben, and the conglomerate clasts were apparently eroded from volcanic rocks that capped the footwalls of the graben-bounding faults. The Eischeid well was drilled off the central horst, and penetrated the fluvial system that drained the rift-bounding Proterozoic terrane. These fluvial systems had their headwaters in the granites and gneisses that dominate the basement of the region, and were the source of the quartz sands that dominate "Unit B".

The middle unit in the "Lower Red Clastic Sequence", Unit C, is almost 1500 feet thick and displays close lithologic and sedimentological similarity to the Nonesuch Shale of the Oronto Group. Both are characterized by gray to black siltstone and shales. Ludvigson and others (1990) identified a number of sedimentary structures that they interpreted as evidence of deposition in a lake or similar standing body of water. Calcite cements and vein fills are more abundant in "Unit C", than in other "Red Clastic" strata in the Eischeid well, and cored intervals display high angle tectonic dips ranging from 65° to vertical and slightly overturned. Ludvigson and Spry (1990) described calcite veinlets and slickensided fault surfaces with rough facets indicating reverse faulting during the later, compression phase of rift development. The presence of such a thick sequence of lake sediments outside of the former central graben suggests that the lakes that formed in the MRS were large, extending well beyond the limits of the graben-bounding faults. Seismic interpretations suggest they may have extended as much as 15 miles beyond the graben (Anderson, 1990c).

Figure 1: Correlation of Eischeid Red Clastics
with the Keweenaw Supergroup

mean framework composition		Eischeid	Keweenaw Supergroup		
?	Q ₇₉ F ₁₇ L ₄	Unit H		?	
Upper Seq.	Q ₇₆ F ₁₇ L ₇	Unit G		Chequamegon SS	Bayfield Gp.
	Q ₈₈ F ₂₂ L ₉	Unit F		Devils Island SS	
	Q ₆₇ F ₂₀ L ₁₃	Unit E		Orienta SS	
Lower Seq.	Q ₇₆ F ₂₁ L ₃	Unit D		Freda Fm	Oronto Gp.
	Q ₇₂ F ₂₄ L ₃	Unit C		Nonesuch Fm	
	Q ₆₇ F ₁₂ L ₁	Unit B		Copper Harbor Fm	

Eischeid Petroleum Potential

Although no shows of liquid petroleum were encountered during the drilling of the Eischeid well, trace amounts of methane and ethane were detected, and rare intergranular black residues (suggestive of oil movement) were observed in the "Lower Red Clastic Sequence". The dark shales and siltstones in the lower sequence were shown by Palacas and others (1990) to once have been organic-rich potential petroleum source rocks, but are presently overmature. Methane clathrates were identified in fluid inclusions in calcite veins by Ludvigson and Spry (1990) who suggested that petroleum was mobile during the compression phase of MRS history. On the basis of comparisons between fluid inclusions and isotope data from vein-filling calcites in the rift-flanking basins (Eischeid oil test) and faults bounding central horsts (Ludvigson and Anderson, 1986), Ludvigson and Spry (1990) suggested that such fluid would be transported towards the flanks of the rift. This petroleum may still be trapped on the flanks of the Midcontinent Rift System.

The M.G. Eischeid #1 well offers a great potential to increase our understanding of the development of the Midcontinent Rift System and the clastic strata associated with it. Also, the rocks encountered in the well demonstrated that large volumes of petroleum was probably generated from organic-rich units and may still be trapped within the structure.

References

- Anderson, R.R., 1990a, The Amoco M.G. Eischeid #1 deep petroleum test, Carroll County, Iowa. Iowa Department of Natural Resources, Geological Survey Bureau, Special Report Series No. 2, 185 p.
- Ludvigson G.A. and Anderson, R.R., 1986, The Douglas Fault at Amnicon Falls State Park, Wisconsin: Brittle cataclastic textures in Keweenawan Rocks. Proceedings of the 32nd Annual Meeting, Institute of Lake Superior Geology, Wisconsin Geological and Natural History Survey, p. 50-51.
- **** all of the following references are in Anderson, 1990a ****
- Anderson, R.R., 1990b, Review of current studies of Proterozoic rocks in the Amoco M.G. Eischeid #1 petroleum test well, Carroll County, Iowa. p. 175-184.
- Anderson, R.R., 1990c, Interpretation of geophysical data over the Midcontinent Rift System in the area of the M.G. Eischeid #1 petroleum test, Carroll County, Iowa. p. 27-38.
- Ludvigson, G.L., McKay, R.M., and Anderson, R.R., 1990, Petrology of Keweenawan sedimentary rocks in the M.G. Eischeid #1 drillhole. p. 77-112.
- Ludvigson, G.L., and Spry, P.G., 1990, Tectonic and paleohydrologic significance of carbonate veinlets in the Keweenawan sedimentary rocks of the Amoco M.G. Eischeid #1 drillhole. p. 153-168.
- McKay R.M., 1990, Regional aspects of the Mt. Simon Formation and the placement of the Mt. Simon - pre-Mt. Simon sedimentary contact in the Amoco M.G. Eischeid #1 drillhole. p. 59-66.
- Palacas, J.G., Schmoker, J.W., Daws, T.A., Pawlewicz, M.J., and Anderson, R.R., 1990, Petroleum source-rock assessment of Middle Proterozoic (Keweenawan) sedimentary rocks, Eischeid #1 well, Carroll County, Iowa. P. 119-134.
- Witzke, B.J., 1990, General stratigraphy of the Phanerozoic and Keweenawan sequences in the area of the M.G. Eischeid #1 drillhole, Carroll County, Iowa. P. 39-58.

THE HOMESTAKE MINE

AN EARLY PROTEROZOIC IRON-FORMATION HOSTED GOLD DEPOSIT

R.L. Bachman
District Geologist
Homestake Mining Company
Lead, South Dakota

The Homestake mine in the northern Black Hills of South Dakota, USA is the largest iron-formation-hosted gold deposit known, and has produced 1,126 tonnes (36.2 million oz.) of gold from 130 million tonnes of ore milled. In 1990 the mine produced 12 tonnes of gold. The deposit was discovered in 1876, and the mine has operated continuously to the present day. Gold ore is currently mined for depths to 2,438 meters. Gold is the principal commodity produced along with a minor silver by-product. The gold/silver ratio averages 5:1; base metal content is negligible.

The deposit lies within the Early Proterozoic core of the Black Hills uplift, which represents the southern most exposure of Trans-Hudson orogen rocks. Tectonism and thermal activity associated with the Trans-Hudson event occurred as a result of the collision of Wyoming and Superior Cratons contemporaneous with the Penokean orogen. Proterozoic gold metallization is interpreted to be a result of an evolved, long lived tecto-thermal process that relied on plate scale shear zones as fluid conduits and zones of high geothermal gradient as fluid mobilizers.

Gold ore bodies at Homestake are hosted almost exclusively by the Early Proterozoic Homestake Formation, an iron-formation (15 to 35% total Fe) consisting of siderite phyllite and/or grunerite schist. The underlying Poorman Formation is composed of an upper sequence of sericite to biotite-dominant carbonate-quartz and graphitic phyllites and a lower voluminous sequence of hornblende-plagioclase schist of tholeiitic affinity. The overlying Ellison Formation consists of sericite-quartz phyllite (pelitic and tuffaceous strata) interbedded with quartzite.

Strata that contain the Homestake deposit were complexly deformed by a series isoclinal and sheath fold events that are synchronous with extensive ductile and ductile-brittle shearing. Mine area rocks have been subjected to upper greenschist-lower amphibolite facies metamorphism; metamorphic intensity increases to the northeast. Intrusion of a 1.72 Ga S-type granite northeast of the mine post-dated regional metamorphism, and appears contemporaneous with late stage semi-brittle deformation (Bachman et al., 1990).

Individual ore bodies are contained within plunging synclinal fold structures of Homestake Formation known as ledges. Ten of these structures have produced gold from relatively undeformed, elongate tabular zones of quartz, siderite, chlorite, pyrrhotite, arsenopyrite, minor pyrite, and native gold. Ore mineralization is developed within and adjacent to dilated segments of late-stage ductile-brittle shears (Caddey et al., 1990). These shears and associated ore bodies cross-cut earlier folds and overprint metamorphic fabric.

At least two stages of mineral alteration are observed, one of which is synmetamorphic and appears to predate gold mineralization, and a second synchronous with gold mineralization. The pre-gold mineral alteration stage is represented by extensive potassium and carbonate metasomatism. Ore-stage hydrothermal alteration appears retrogressive producing extensive chlorite and siderite replacement of the Homestake Formation in and adjacent to the ore bodies.

Timing of gold mineralization at Homestake, even though not dated directly, is regarded as early Proterozoic. Dating of zircon from tuffaceous sediments within the Ellison Formation gave an age of 1.97 Ga (Redden et al., 1990) and provide an approximate age for Homestake Formation deposition. The approximate age of regional metamorphism and major regional ductile deformation is 1.84 Ga (Zartman and Stern, 1967). The Crook Mountain Granite and associated deformation at 1.72 Ga appears to post-date gold mineralization. It is interpreted that gold was introduced after peak metamorphism (1.84 Ga) and prior to granite emplacement (1.72 Ga) by epigenetic processes.

REFERENCES

- Bachman, R.L., Campbell, T.J., and Sneyd, D.S., 1991, Crook Mountain granite and its relation to Early Proterozoic gold mineralization at the Homestake mine, northern Black Hills, SD: *Geol. Soc. America, Abstracts with Programs*, v. 22, no. 6, p.2.
- Caddey, S.W., Bachman, R.L., Campbell, T.J., Reid, R.R., Otto, R.P., 1990, The Homestake gold mine, an Early Proterozoic iron-formation hosted gold deposit, Lawrence County, South Dakota: *U.S. Geol. Survey Bull.* 1857-J (in press).
- Redden, J.A., Peterman, Z.E., Zartman, R.E., and DeWitt, E., 1990, U-Th-Pb geochronology and preliminary interpretation of Precambrian tectonic events in the Black Hills, South Dakota: *Geol. Assoc. Canada Spec. Paper on the Trans-Hudson Orogen* (in press).
- Zartman, R.E., and Stern, T.W., 1967, Isotopic age and geologic relationships of the Little Elk Granite, northern Black Hills, South Dakota; *U.S. Geol. Survey Prof. Paper* 575-D, p. D157-D163.

EXTENSION OF GRAVITY FILED COVERAGE IN EAST-CENTRAL
WISCONSIN: 1990 COGEOMAP PROGRAM

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During the summer of 1990, approximately 4800 additional measurements of the earth's gravity field were made in an area bounded by 44 & 45 degrees latitude and by 88 & 90 degrees longitude. Most stations are located at surveyed elevation points posted on USGS topographic sheets and are spaced one mile apart, except where access was limited. Northern Illinois University's LaCoste-Romberg gravity meter G409 was used. Data are tied to the State of Wisconsin Primary Gravity Base Station Network (Ervin, 1983), which is in turn tied to the International Gravity Standardization Network-1971 (DMAAC, 1974). Normally accepted field and processing procedures were used. These data have been combined with earlier data to produce a much more detailed Bouguer gravity anomaly map.

The northwest section of the area is underlain by primarily Proterozoic and Late Archean rocks, comprised of quartzite, granite, rhyolite, granodiorite, gneiss, metavolcanics, and metasediments. This variability is reflected in the complex character of the Bouguer gravity anomalies.

The north-central part of the region contains the southern part of the Middle Proterozoic Wolf River Batholith, which is composed primarily of granitic and syenitic rocks, with inclusions of quartz monzonite, anorthosite, and gabbro. The greater homogeneity of the Wolf River Batholith produces a smoother Bouguer gravity field than exists in the northwest section.

The southern and eastern areas of the map largely overly Paleozoic sedimentary rocks, possibly underlain at depth by an extension of the Wolf River Batholith (Allen, 1990), resulting in a Bouguer gravity field dominated by longer wavelength anomalies than in the rest of the survey region.

REFERENCES

- Allen, D.J., 1990, The Wisconsin Gravity Minimum: Source and Implications, unpub. MS thesis, Purdue Univ., West Lafayette, IN., 183 p.
- Ervin, C.P., 1983, Wisconsin Gravity Base Station Network, Wis. Geol. & Nat. Hist. Surv. Misc. Pap. 83-1, 43 p.
- DMAAC, 1974, World Relative Gravity Reference Network - North America, DMAAC Ref. Pub. No. 25, 1974 Supplement.

Nonmetallic Mineral Resources and Minor Metals Potential of Northern Wisconsin

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The Precambrian terranes of northern Wisconsin contain significant nonmetallic mineral resources and have the potential for other metal deposits in addition to volcanic-hosted massive sulfides. The region has a long history as a producer of building and ornamental stone and a variety of crushed stone products. Other products include weathered or "rotten" granite and clay from weathered crystalline rocks and glacial deposits. Northern Wisconsin contains potentially economic occurrences of industrial minerals (talc, graphite, marble, kyanite, nepheline syenite, silica sand, and others) and rare metals (molybdenum, beryllium, lithium, and others). Significant deposits of iron are also present but are not currently economical to produce.

In recent years, dimension stone production has maintained a low but steady level of activity; the crushed stone industry has grown significantly. This growth has been in response to a growing demand for high quality railroad ballast and changing construction specifications that require higher quality aggregates for base course and asphalt paving mixtures. Specialized operations produce crushed metavolcanic rock for roofing granules and aggregates for terrazzo stone and synthetic granite production.

Although base and precious metal potential has attracted much attention recently, the nonmetallic minerals have long been and will continue to be a major economic resource of northern Wisconsin. Important factors are a good transportation network and Wisconsin's favorable location in respect to markets in the upper Midwest. The future development of regulatory framework on the state and local level will have important implications for future development of this industry.

Preliminary Bedrock Geologic Map of Eau Claire County, Wisconsin

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Wisconsin Geological and Natural History Survey

Eau Claire County is underlain by rocks ranging from Early Proterozoic and Archean (?) to Late Cambrian age. Precambrian rock is exposed in scattered outcrops along the Eau Claire River and tributaries in northeastern Eau Claire County. The Precambrian consists of a suite of amphibolites and granitic gneisses of possible Archean age, and what is probably a younger sequence of metavolcanic and metasedimentary rocks and granitic intrusions of probable Penocean (1850 Ma) age. Underformed mafic dikes cut older units and may be as young as Keweenaw.

The Precambrian is overlain by Upper Cambrian clastic and carbonate rocks of the Elk Mound, Tunnel City, and Trempealeau Groups. The Upper Cambrian contains two fining-upward sedimentary cycles. The lower cycle consists of the basal Mount Simon sandstone that grades upward into the glauconitic Tunnel City Group and sandy dolomite of the St. Lawrence Formation.

Eau Claire County has no historical record of mineral production from the Precambrian. Residual clay is associated with the Cambrian/Precambrian unconformity, and the Wonewoc Formation is a potential source of silica sand. The only Paleozoic unit potentially suitable for aggregate is the St. Lawrence dolomite, which is present only on ridge tops in the southwestern area of the county. Pleistocene alluvial deposits along the Chippewa and Eau Claire Rivers are the primary source of construction materials. Principal aquifers are the alluvial deposits and the Mount Simon sandstone.

Collision Induced Ripoffs, Ancient and Modern:
The Midcontinent Rift System and the Red Sea-Gulf of Aden
compared.

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517-355-4626)

Slab pull is considered to be a major force in determining the rate and directions of plate motion. Irregular or oblique convergence will result in closure of an ocean at some localities prior to others. Once a portion of the subducting plate has sutured, the plate will slow down or stop. Adjacent, unclosed sections of oceanic crust, however, will continue subduct under the influence of slab pull (fig.1.1). This may result in tensional stresses in a portion the subducting plate. Since fractures are more likely to develop in the weaker, continental part of the subducting plate, a fragment of the plate may be detached along an intracontinental rift system (fig.1.2). Opening of this rift system would be limited to a small ocean basin since continuing subduction will close the remaining portion of the original ocean basin. Closure of the original ocean basin, could then result in compression in the rift system (fig.1.3). This sequence explains the near synchronous association of extension and compression, and the subsequent deformation of the rift fill, as found in many once extensional regions.

The Red Sea is a modern example of this process. Closure of the Tethys occurred first in the Mediterranean and left a portion of the African plate, with attached oceanic crust, still subducting under the Zagros region. Continuing slab pull in this region, combined with the restraint to the west, induced the detachment of the Arabian Peninsula along the Red Sea and Gulf of Aden (fig.2). Extension in the Proterozoic Mid Continent Rift system of North America was coincident with the Grenville compressional event to the south and east. The rift experienced only limited opening which we suggest was due to slab-pull along an unclosed segment in the collision zone of the Grenville Orogenic belt (fig.3). Subsequently, the entire collision zone closed and the rift was pushed back into place giving rise to a complex pattern of folds and flower structures (fig.4).

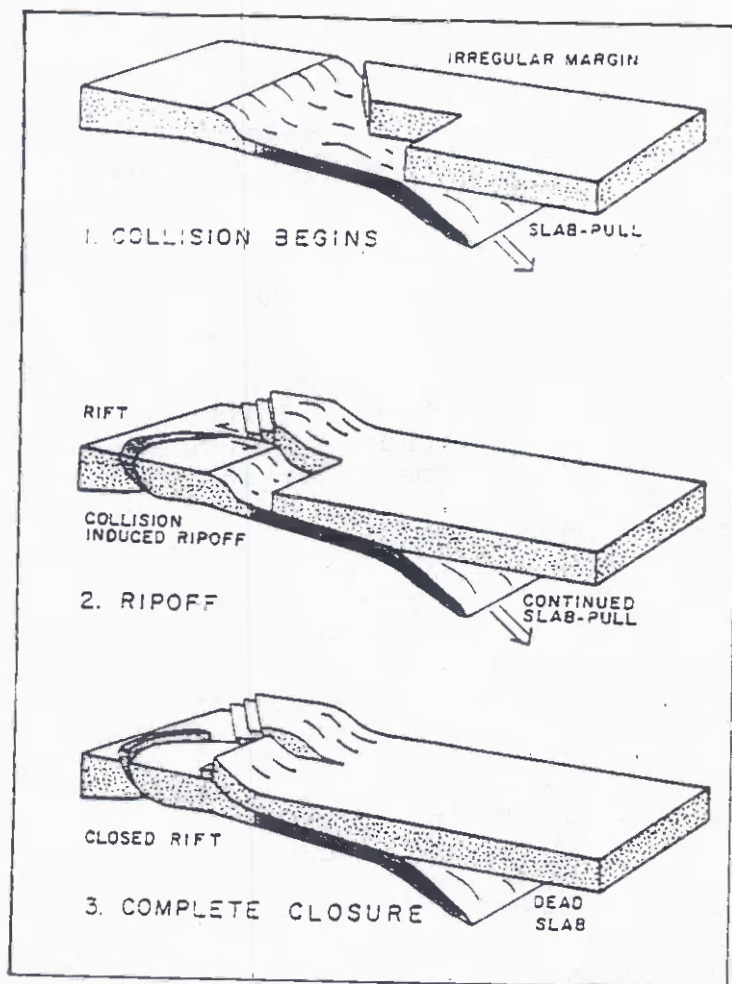


Fig. 1

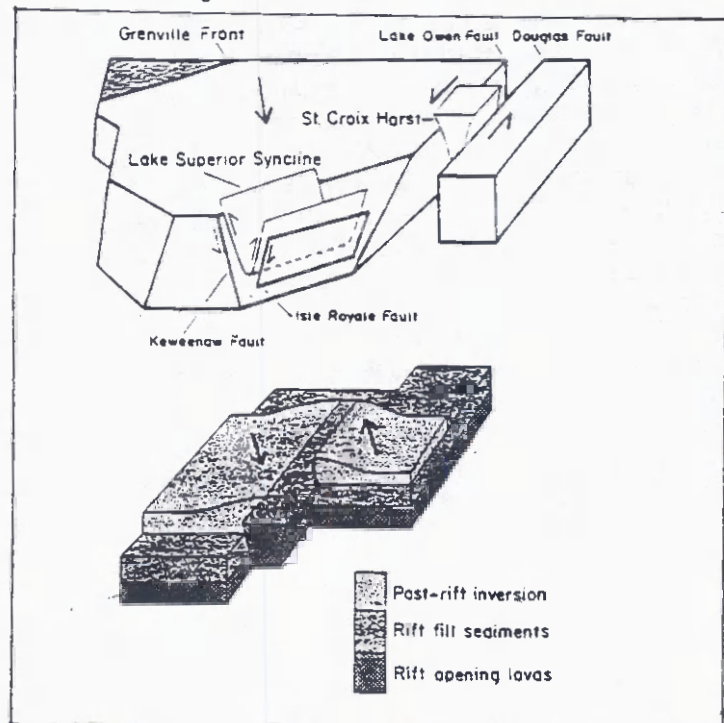


Fig. 4

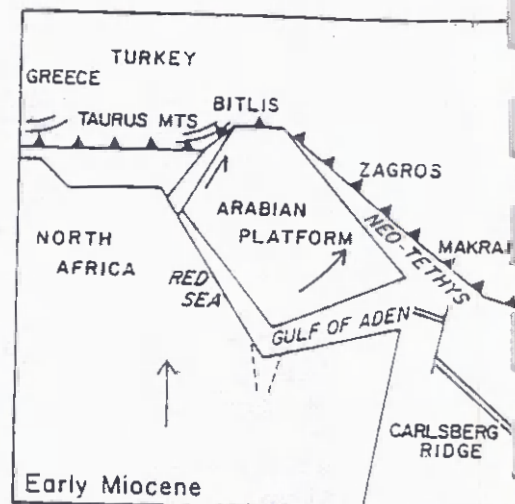


Fig. 2

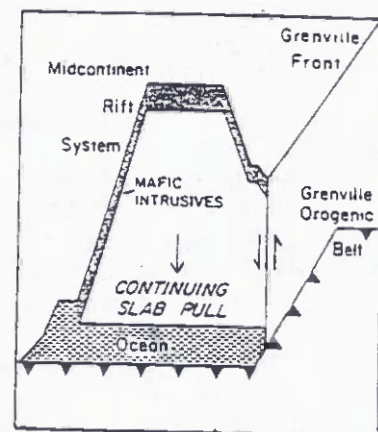


Fig. 3

DETACHMENT FAULTING AND THE ORIGIN OF THE ASYMMETRIC DEPOSITIONAL PATTERN OF THE MARQUETTE TROUGH. F. William Cambray, Dept of Geological Sciences, Michigan State University, East Lansing MI 48824., Joseph J. Mancuso, Dept. of Geology, Bowling Green State University, Bowling Green, OH 43403., and Went Slitor, C.C.I., 504, Spruce Street, Ishpeming, MI 49849.

The Marquette Trough is one of several fault bound basins set into the Archean crust of northern Michigan which contain Lower Proterozoic metasedimentary rocks. The pattern is interpreted as deposition in rift basins associated with the development of a passive margin prior to the Penokean Orogeny. The orogeny was triggered by collision of an island arc to the south. Deposition in the trough began with the Siamo Formation which consists of alternating layers of pelite and arenite, the latter having turbidite characteristics. This was followed by a thick sequence of banded iron formation, the Negaunee BIF. The iron formation is interbedded with clastic lenses which thicken and become more frequent towards the southern margin suggesting provenance from this direction, sole marks indicating a turbidite origin have been found at the base of these layers. The clastic lenses are somewhat irregular in distribution and disappear rather abruptly to the north. Changes in the pattern of clastics is often associated with faults. This pattern is similar to asymmetric fault basins which have been described in relation to major crustal detachment faults in the Cenozoic of the Western US (fig. 1). The overall stratigraphic pattern suggests that such a detachment may be present. On the south side the stratigraphy is truncated adjacent to the margin which is consistent with continual displacement during sedimentation whereas the succession is more continuous across the margin of the trough (fig. 1). The Palmer Gneiss is a candidate for the main detachment fault on the south side. Outcrops of the gneiss close to the contact with the Proterozoic rocks are broken and contain chlorite, this lithology passes into a banded gneiss to the south near the Tilden Mine. The banding consists of normal gneissic texture interspersed with mylonite. This association is similar to the description of detachment surfaces in the western US. The chlorite rich material represents the high level breccia which formed in the brittle zone and the banded mylonite is the deeper ductile portion of the detachment fault. The two were brought together by a large normal displacement. The Penokean Orogeny complicated the picture, reactivating some of the normal faults as reverse faults but the basic pattern is still recognizable (fig. 2).

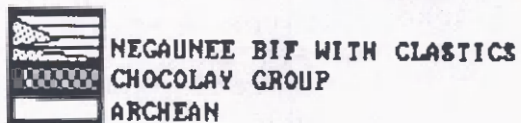
ASYMMETRY OF THE MARQUETTE TROUGH (Cambray and Mancuso, 1991)



Fig. 1 Extension



Fig. 2 Penokean Compression



A LATE KEWEENAWAN THRUST ? MARQUETTE COUNTY, MICHIGAN.
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Records from a drill hole on the southern margin of the Marquette Trough (Hole M30, sec. 17 T47N R25W, Sands Quadrangle. Core made available by CCI Ishpeming.) describe a 'Cambrian clastic dike' occurring at a depth of 360 feet. The overlying material is deformed and metamorphosed Proterozoic Kona Formation. Re-examination of the 'dike' has shown that it is an immature, poorly sorted unmetamorphosed quartz arenite containing fragments of the Kona Formation. The lithology is very similar to the local outcrops of Jacobsville Sandstone. Although the Jacobsville has been described as Cambrian in the past it is now widely believed to be late Keweenawan in age. A re-examination of the core reveals that the sandstone bedding is vertical and the fragments of Kona Formation included in the sandstone are aligned parallel to this vertical bedding. All the exposures in the immediate region are Lower Proterozoic rocks, mostly Kona Formation.

We interpret the pattern observed in the drill hole to indicate a late Keweenawan thrust placing the Kona Formation over the Jacobsville (fig.2). During the Keweenawan widespread rifting produced clastic filled basins throughout the Lake Superior region. Towards the end of the period the Jacobsville Sandstone, and the equivalent Bayfield Group formed a widespread blanket over much of the region. This was followed by a compressional event which gave rise to thrust faulting on the Keweenaw Peninsula and several reverse faults in the Midcontinent Rift section of Wisconsin and Minnesota. Until now there has been no record of this late compressional event east of the Keweenaw Peninsula. The sequence of events proposed is as follows.

- 1) Extensional tectonics associated with the opening of the Midcontinent Rift System produced a rift basin above the Marquette Trough which filled with sediment derived from the surrounding Archean Basement and the Proterozoic metasediments (fig. 1). The sediments contain unweathered microcline and fragments of mylonite from the gneisses. Pelite lenses mark the bedding surface and compaction structures are clearly visible. Fragments of the Kona Formation up to 5 centimeters long by 2 centimeter wide are aligned parallel to the bedding. The poor sorting suggests that this locality was close to the fault scarp.
- 2) The compressional event produced in a thrust close to the original rift margin and transported the adjacent Kona Formation over the Jacobsville basin, tilting the sandstone to its present vertical position in the process (fig 2).

This pattern of deformation in the late Keweenawan is not surprising considering the structures seen to the west. If it is more widespread it adds another factor to be considered when attempting to unravel the structure of the older Proterozoic in the Great Lakes region.

LATE KENEENAWAN THRUSTING, MARQUETTE MICHIGAN
Cambray and Scott 1991

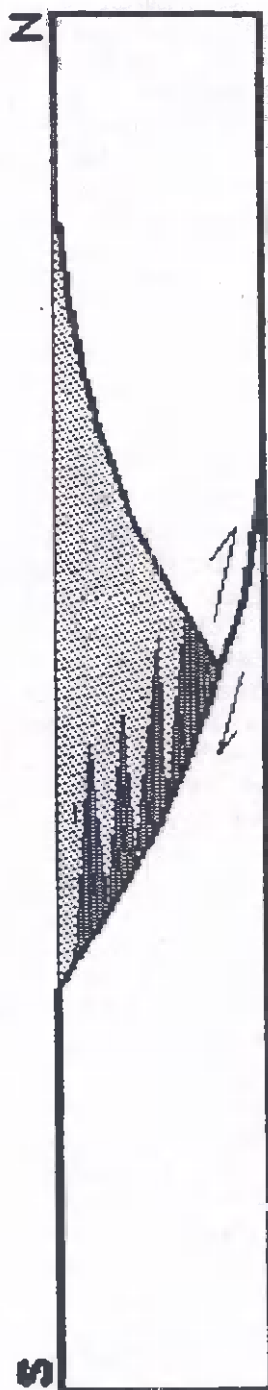


Fig. 1 Rifting Phase

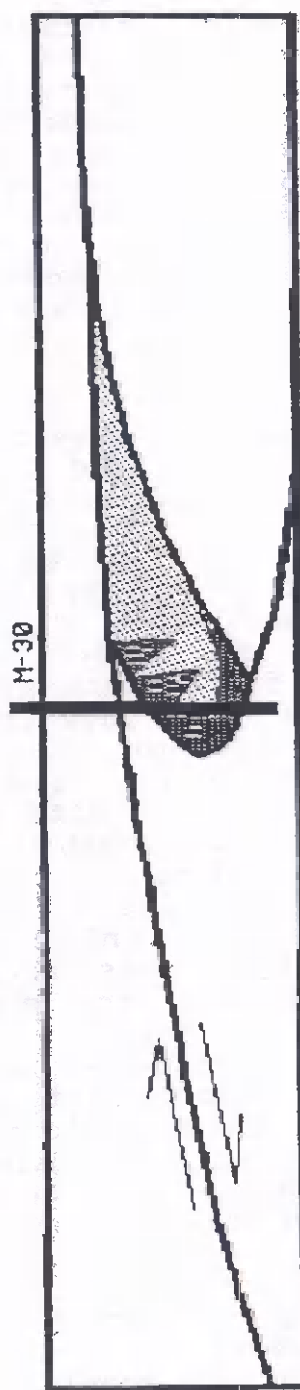


Fig. 2 Compressional Phase

Jacobsville Sst.
with coarse lenses
Kona Fm.

The Feasibility of Recovering Metals From a Hazardous Waste Site
A (Brief) Case Study

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The National Lead (NL)/Taracorp/Golden Site (Site) is located in St. Louis Park, Hennepin County, Minnesota. The Site is approximately 10 acres in size and is the former site of a secondary lead smelter. The Site is included in the U.S. Environmental Protection Agency's (EPA's) National Priorities List (NPL) and is also present on the Minnesota Pollution Control Agency's (MPCA's) Permanent List of Priorities (PLP). The secondary smelter was operated by NL and Taracorp between 1940 and 1981, and was used to reprocess lead, lead oxide and lead sulfate from batteries and scrap into various lead alloys. The main solid waste produced by the smelter was slag from the blast furnace which was deposited on-site between 1940 and 1962. The presence of the lead-bearing slag in the sub-surface constitutes a potential threat to the local surficial and bedrock aquifers, and is the main reason for the inclusion of the Site on the NPL and the PLP.

The slag, which is a major component of the fill materials on the Site, is heterogeneous in nature. Limited analytical data indicate that the slag contains up to 45,900 part per million (4.5 percent) lead. Visual inspection of slag samples indicates a high iron content in some samples, while other samples have a high lead (galena) content. Approximately 16,000 cubic yards of fill materials are present on the Site, and it is estimated that 25 to 90 percent of the fill is slag.

The current remedy for the Site is an asphalt "cap", installed in 1988 which was designed to prevent infiltration of precipitation and thereby prevent leaching of lead from the slag. The EPA is currently engaged in a five-year review of the Site, which is required by the Superfund program (Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)). This review process will consider the status of the Site and the risks represented by the hazardous materials (slag) that remain on the Site. In this context, other more permanent remedies such as encapsulation, fixation or excavation and removal may be considered by the EPA and the MPCA. An alternative permanent remedy which merits consideration is the recovery of lead and other metals (Cd, As) from the slag. Technical, regulatory and economic barriers must be overcome in order to make the recovery of lead from the slag a feasible alternative.

Technical barriers to the recovery of lead from the slag revolve around the heterogeneous nature of the slag and the variable iron, lead and silica content of the slag. The U.S. Bureau of Mines, through its Environmental Technology Research Program, has investigated the possibility of recovering lead from mill tailings in Missouri. Approaches such as an air sparged hydrocyclone show promise and may also permit recovery of lead from slag. Another technique, utilizing a flame reactor process, has been evaluated by the EPA in its Superfund Innovate Technology Evaluation (SITE) Program.

Regulatory barriers to the recovery of lead from the slag are related to the involvement of two major statutory authorities. The Resource Conservation and Recovery Act (RCRA) and CERCLA may both regulate this type of remedial activity at the Site. Definitions of hazardous waste and cleanup standards are complex issues in this context and must be clarified in order to make recovery of lead from the slag a feasible permanent remedy.

Economic barriers to the recovery of lead from the slag at the Site are similar to those that are faced during the development of an ore deposit. The costs for excavation, removal and transportation of the slag to a smelter will probably be substantial given the volume, distribution and heterogeneous nature of the material. The metallurgical problems in separating the lead from the slag may be significant. The economic incentive for completing this type of permanent remedial action is the prospect of industrial/commercial development of the Site.

PALEOMAGNETISM OF CENTRAL WISCONSIN DIKE SWARM: CONSTRAINTS ON THERMOMECHANICAL MODEL OF MIDCONTINENT RIFT

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Five mafic dikes in central Wisconsin were sampled for paleomagnetic determinations. The paleopoles obtained reveals more than one dike intrusion episode. The preliminary paleomagnetic results can be divided into two groups. The mafic dikes in Marathon City, Big Falls Park, and Little Falls Park in Eau Claire County yield a cluster of paleopoles that lie near the 1.1 Ga paleomagnetic pole of the North American craton. The paleopoles of the dikes in Lake Wissota and Jim Falls in Chippewa County are about 1.0 Ga. The lack of intermediate poles implies episodic dike intrusions. Similarly, Keweenawan dike swarms and volcanic units in the Lake Superior area also show an episodic nature. The determination of the intrusion ages is conducive to our understanding of the thermomechanical state of the midcontinent rift. The dike swarm is located about 200 km from the rift axis. The recurrence of dike intrusion activities at such a far distance from the rift axis implies oscillation between strong tensile stress during the intrusive stages and weak tensile or compressional stress during the inter-intrusive stages. Such variation in stress likely resulted from fluctuation in magmatic activity along the rift axis.

AEROMAGNETIC SURVEYING PROGRAM IN MINNESOTA: PAST AND FUTURE PERSPECTIVES

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The high-resolution aeromagnetic surveying program of the Minnesota Geological Survey (MGS), which began in 1979 with support from the Legislative Commission on Minnesota Resources (LCMR), will be completed in 1991. In addition to the LCMR-sponsored data, data have been contributed by the U.S. Geological Survey and the Geological Survey of Canada for north-central Minnesota and by USX Corporation for southwestern Minnesota. When complete, the statewide aeromagnetic data base will be the only one of its kind in North America to encompass a relatively large area with such detail. All surveying to date has maintained nearly the same specifications, the key ones being close flight-line spacing (400–500 meters) and low terrain clearance (150–200 meters). In the present survey over southeastern Minnesota, some data can be flown at 1000-meter spacing, owing to burial-related smoothing of anomalies from Paleozoic strata.

The data, which have already served a broad spectrum of economic and scientific interests, are available as 1:24,000-scale contour maps, 1:250,000-scale contour and color maps, and as digital tapes of flight-line and gridded data.

Use of the aeromagnetic data in conjunction with test drilling has led to several major revisions of the Precambrian geology of Minnesota, most of which lies concealed beneath a thick mantle of Pleistocene glacial materials. Inverse modeling of aeromagnetic anomalies and Poisson analysis of gravity and magnetic data have assisted significantly in a recent reinterpretation of the Early Proterozoic Penokean orogen in east-central Minnesota. Aeromagnetic data have been consistently used in interpreting the partially exposed Archean greenstone-granite terrane of north-central Minnesota. Derivative-enhanced aeromagnetic and gravity data have been used to interpret the geology of the poorly exposed central part of the Middle Proterozoic Duluth Complex of northeastern Minnesota. In northern and central Minnesota, aeromagnetic data are being used to investigate a major dike swarm of Early Proterozoic age. The Minnesota Geological Survey plans further interpretive work in the Archean greenstone-granite terrane of northwestern Minnesota, the Archean gneiss terrane of southwestern Minnesota, and the Middle Proterozoic Duluth Complex.

Looking to the future, several major tasks related to aeromagnetic surveying remain. In a recent workshop hosted by the MGS and sponsored by the LCMR, several recommendations were made for future geophysical work in the state. Among the recommendations pertinent to aeromagnetic surveying were (1) to accelerate processing and interpretation of aeromagnetic data in conjunction with test drilling and geologic mapping; (2) to make the digital aeromagnetic data available in more diverse media than presently available, with emphasis on PC-based technology; and (3) to expand the MGS physical-property data base on Minnesota's bedrock and glacial sediments. The MGS plans to pursue these recommendations aggressively.

In the broader perspective of the Midcontinent region, much remains to be done. In most areas the aeromagnetic coverage is simply inadequate, especially with regard to flight-line spacing versus depth to basement. The tremendous success of the aeromagnetic surveying program in Minnesota presents a strong incentive for other state or federal agencies working in the Midcontinent region to pursue similar programs.

CONTINUOUS STRIKE-SLIP FAULT-EN ECHELON FRACTURE ARRAYS IN
DEFORMED ARCHEAN ROCKS: IMPLICATIONS FOR FAULT PROPAGATION
MECHANICS

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Abstract

A regional strike-slip and en echelon fracture array (orientation: N-S, 90) is observed in three dimensions in Archean rocks in northern Minnesota, northern Michigan, and western Wisconsin. Distinct fault planes (Mode I) change along strike into single or conjugate en echelon fracture arrays (Mode II) resulting in an undulating fault trace with an average amplitude of ~5 cm and wavelength of ~1 m. Both dextral and sinistral displacements are found in the same outcrop, and fault displacements change along strike. Brittle en echelon shear sense indicators generally compliment the observed fault displacement, but not always.

Mode I and II fractures cut and cross-cut each other and are thus contemporaneous features, indicating that the Mode I extensional fractures became strike-slip faults where initially the maximum principal compressive stress (σ_1) was parallel to the strike-slip fault. Mode II en echelon sets can be used as shear sense indicators for the strike-slip faults however, displacements along individual Mode II fracture planes are opposite that of the strike-slip fault. The undulating fault planes resulted from the interaction between propagating Mode I fractures and Mode II en echelon shear fracture pods, both of which are three dimensionally continuous and locally out-of-phase. Timing constraints on these fault systems, which are regionally distributed in Archean rocks of the Great Lakes region, indicate a post-2.6 BY and pre-1.1 BY age for this deformation.

PRELIMINARY DRILL CORE STUDY OF TWO HOLES DRILLED ON THE CUYUNA IRON
RANGE AND EMILY MANGANIFEROUS IRON FORMATION DISTRICT OF MINNESOTA

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Two diamond drilled core holes were recently completed in manganiferous iron formations in Central Minnesota--one on the Cuyuna Range and one in the Emily District. The purposes for drilling were first to obtain drill core for geologic characterization and whole core leaching experiments, and subsequently to conduct geophysical logging and hydrologic flow testing. This drilling program was cost-shared by the U.S. Bureau of Mines and the University of Minnesota-Mineral Resources Research Center under a Bureau Cooperative Agreement and is part of the Bureau's ongoing research on in situ mining of critical and strategic minerals. The information gathered from these two holes will be used in the evaluation of whether or not in situ mining techniques can be utilized to recover manganese from the manganiferous iron formations in Central Minnesota.

In situ mining involves the use of fluids to remotely solubilize and mobilize target metals in an ore deposit and transport them to the surface via recovery wells where the fluids can be directly processed for metal recovery. The success of an in situ mining operation depends to a large degree on whether the target ore minerals can be selectively dissolved and whether the dissolved target metal can be transported to the production wells via fluid flow channels. The degree of success is governed by the inherent chemical and physical characteristics of the ore body such as the types of ore minerals, types and abundance of reactive gangue minerals, kinetics of ore and gangue mineral dissolution, ore zone permeability, proximity of ore minerals to the fluid path, and groundwater flow characteristics in both saturated and unsaturated deposits. At the microscale, the relationships between the ore and gangue minerals, particularly texture and composition, are very important. Low target metal recoveries will occur if the leach solution cannot contact the target ore minerals regardless of how well the leach chemistry is optimized. For example, target ore minerals may be encapsulated by unreactive gangue or short circuiting of leach fluid may occur due to structural controls such as joints and microfractures. Also, fluid pathways may be plugged by clay swelling or accumulation of mobilized particles. This type of information obtained through a petrographic study of preleach and postleach ore samples provides valuable guidance in predicting in situ mining metal recoveries and the feasibility of in situ mining for a prospective ore body.

Bureau research is providing new insights into predicting in situ mining metal recoveries. Potential problems and constraints are being identified and modeled before field leach mining tests are initiated. As part of this research, the Bureau is conducting a geologic characterization study of the drill core from the Cuyuna Range and Emily District which includes: stratigraphy, gangue and ore mineralogy, textural relationships, assays, detailed whole rock chemical analyses of selected samples, permeability and porosity, fracture analysis, and magnetic susceptibility. A combination of laboratory geologic characterization techniques are being used on whole core samples to determine ore/gangue and structural relationships of preleach and postleach material. These techniques include petrographic analysis of polished thin sections, scanning electron microscope imaging, electron microprobe analyses, and X-ray diffraction.

Hole G-1 from the Cuyuna Range was drilled on the National Steel Corporation's former Gloria underground mine site near Ironton, MN, located in the northwest 1/4 of the southeast 1/4 of the southeast 1/4 of Section 28, Township 47N, Range 29W, Crow Wing County. This hole was drilled to a depth (along the incline) of 1200 ft at an inclination of 55 degrees to the north-northwest. Hole E-1 was drilled on public land near Emily, MN, and located in the southeast 1/4 of the southwest 1/4 of the northwest 1/4 of Section 21, Township 138N, Range 26W, Crow Wing County. This hole was vertically drilled to a depth of 787 ft.

The following descriptions of the stratigraphy from each hole are based solely upon hand sample observations. Detailed petrographic analyses are currently ongoing.

HOLE G-1

Depth, ft (along the incline)

- 0 - 85 Glacial surficial material

- 85 - 202 Rabbit Lake Formation - Dark to medium-dark gray carbonaceous argillite, locally mineralized with < 1-2% marcasite and pyrite, contains minor 0.2-mm to 15-cm thick clastic beds which are variably hematitic.

- 202 - 1167 Trommald Iron Formation
 - 202 - 438 Thick-bedded facies - Massive and mottled appearing beds (2-5 cm and up to 1.5 m) of intermixed goethite, limonite, and hematite with locally occurring thin-bedded clastics (< 1 mm thick) and massive to thin-bedded chert. Manganese mineralization begins at 243 ft.

 - 438 - 659 Mixed thick- and thin-bedded facies - Massive to mottled to thin-bedded iron formation consisting of interbedded goethite, limonite, hematite, and manganese oxides with minor locally-occurring argillized clastics and oolitic chert.

 - 659 - 1167 Thin-bedded facies - Oxidized interval (659-922 ft) consists of alternating thin beds (0.2-5 mm and up to 1 cm thick) of hematitic/goethitic iron formation, argillized clastics, chert, and magnetite. The transition from oxidized to reduced iron formation occurs from 922-943 ft. Reduced iron formation (943-1167 ft) consists of very fine-grained, thinly-bedded (0.5 mm - 2 cm thick) alternating dark to light gray to dark greenish gray bands. The unit contains minor thin (0.5 mm - 3.5 cm) chert and clastic interbeds. Magnetite beds are partially oxidized to hematite above 913 ft.

- 1167 - 1200 Mahnomen Formation - Medium to light gray, massive to weakly bedded, sericite-quartz semischist with $\leq$ 7% dark mafic porphyroblasts that are 0.25-1 mm in diameter.

Hole G-1 was drilled along cross section "A-A" on Plate 3 described in "Geology and Ore Deposits of the Cuyuna North Range, Minnesota" by Robert Gordon Schmidt, U.S. Geological Survey Professional Paper 407, 1963, 96 pp. Schmidt suggested that the contact between the Trommald Iron Formation and the underlying

Mahnomen Formation was folded. Using this interpretation, hole G-1 should have contacted the Mahnomen Formation at approximately 760 ft depth along a 65-degree incline. Hole G-1 located the contact between these two formations at 1167 ft which is approximately 400 ft lower than proposed by Schmidt, thereby proving that the proposed fold is not present. Also, the oxidized zone in the upper part of the Trommald Formation extends deeper (about 800 ft below bedrock surface) than previously described by Schmidt.

HOLE E-1

Depth, ft

- 0 - 169 Glacial surficial material
- 169 - 321 Ferruginous graywacke - Light to medium-gray, well-bedded (1-5 mm) clastics consist of fine silt- to medium sand-sized grains of quartz, argillized feldspar, and disseminated hematite in a clay-rich matrix. Irregular, mottled-appearing iron oxide staining loosely follows bedding and fractures in 1 mm to 5 cm bands. Argillization varies from slight at the top of the bedrock (221-305 ft) to extreme at the bottom of the unit (310-321 ft).
- 321 - 437 Cherty iron formation - Consists of massive white chert with disseminated clots (1-5 mm diameter) of hematite and goethite interbedded with predominantly massive to thinly bedded hematitic iron formation. Towards the top of the unit, the chert is thin and irregularly bedded (321-328 ft). Thin, argillized clastic beds (1-10 mm) are interbedded with iron formation from 337-350 ft.
- 437 - 734 Manganiferous iron formation - From 437-584 ft, the unit consists of hematitic, manganiferous, thin-bedded to massive iron formation with minor oolitic to massive chert interbeds. Manganese oxides occur in zones intermixed with hematite and as beds and irregular lenses (1 mm - 3 cm thick). From 584-734 ft, the unit consists of thin to thickly (1 mm - 10 cm) interbedded hematitic and goethitic iron formation, chert, and manganese oxide-rich beds with intervals where iron formation, chert, or manganese oxides predominate.
- 734 - 761 Manganiferous chert - Oolitic granule-rich chert. Sooty manganese oxides locally replace oolites and the matrix as irregular vuggy patches. A medium grey, massive chert bed (80 cm thick) occurs at 765 ft.
- 761 - 763 Argillized thin-bedded slate - Argillized, finely bedded (1 mm - 2 cm) slate consists of medium- to fine-grained clastics with disseminated hematite pseudomorphs after magnetite octahedra. Localized iron-oxide staining generally follows bedding.
- 763 - 767 Manganiferous chert - Same as 734-761 ft.
- 767 - 787 Argillized thin-bedded slate - Same as 761-763 ft.

The stratigraphy of hole E-1 identified that the dip of the sedimentary layers in this area flatten to the north. The information from this hole was added to the geologic database of holes previously drilled (approximately 40 years ago) to further define the stratigraphy of the Emily district.

GEOLOGIC SETTING OF THE EARLY PROTEROZOIC
BASE- AND PRECIOUS-METAL-RICH METAVOLCANIC BELT
OF WISCONSIN

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Since the late 1960s, measured and inferred resources of over 100 million short tons of volcanogenic massive-sulfide mineralization have been discovered in northern Wisconsin. The largest deposit, near Crandon, was identified by Exxon Minerals and contains approximately 75 million short tons of ore averaging 5% zinc, 1.1% copper, and 0.4% lead. The most recent discovery was made by Noranda Exploration Inc. at Lynne, in Oneida County. One of their discovery holes contained a 128-foot intercept grading 22.7% zinc, 0.64% copper, and 2.95% lead. Significant precious metal values are associated with many of the known deposits.

The deposits occur within the Early Proterozoic Penokean fold belt (1850-1900 Ma) which has been divided by Greenberg and Brown (1983) into two major terranes: the northern terrane supported by a supra-crustal sequence deposited on the Archean basement (Sims' Continental Margin assemblage; Sims and others, 1989) and a southern terrane composed of volcanogenic rock and Early Proterozoic granite intrusives. This southern terrane, the Wisconsin Magmatic Terrane (also known as the Wisconsin Penokean volcanic belt), is characterized by an island-arc basin assemblage containing abundant calc-alkaline metavolcanic units and associated lesser amounts of metasedimentary rock. Sims and others (1989) have further divided the Wisconsin Magnetic Terrane into two volcanic arc terranes on the basis of lithology and structure; they include the northern Pembine-Wausau terrane and

the Marshfield terrane to the south. The three terranes are believed to be separated from one another by major paleosuture zones (Niagara Fault, Eau Claire Shear Zone).

The Pembine-Wausau arc sequence is the focus of base- and precious-metal exploration activity that has resulted in the discovery of a number of massive-sulfide deposits and occurrences. The dominant volcanic complex in this terrane, based on regional gravity and magnetic data, has been referred to informally as the "Ladysmith-Rhineland greenstone belt". At its western end, the complex can be further subdivided into three major regional units, based on geophysics and known lithology. They include a central volcanic-arc sequence that defines the structural core of the complex, a marginal back-arc basin sequence, and a number of major felsic centers (DeMatties, 1989). These units may correlate with LaBerge and Myers' (1984) amphibole-greenschist succession in the Wausau and Eau Claire areas.

Within this geologic framework, three distinct geologic environments appear to host massive-sulfide mineralization: (1) syngenetic strata-bound and stratiform sulfide mineralization within, along the flanks of, or near the stratigraphic top of the felsic centers; syngenetic strata-bound and stratiform massive-sulfide mineralization associated with cherty magnetic iron-formation and located in the main volcanic arc sequence; and epigenetic stringer-sulfide mineralization and syngenetic strata-bound and stratiform massive-sulfide mineralization associated with mafic piles within the back-arc basin sequence. Based on our present knowledge of the region, the three defined host environments and their association with meta-argillite formations appear to be major regional features controlling the localization of metal-bearing massive-sulfide mineralization in

the western part of the complex. Other host environments will undoubtedly be identified as exploration continues in the complex.

References:

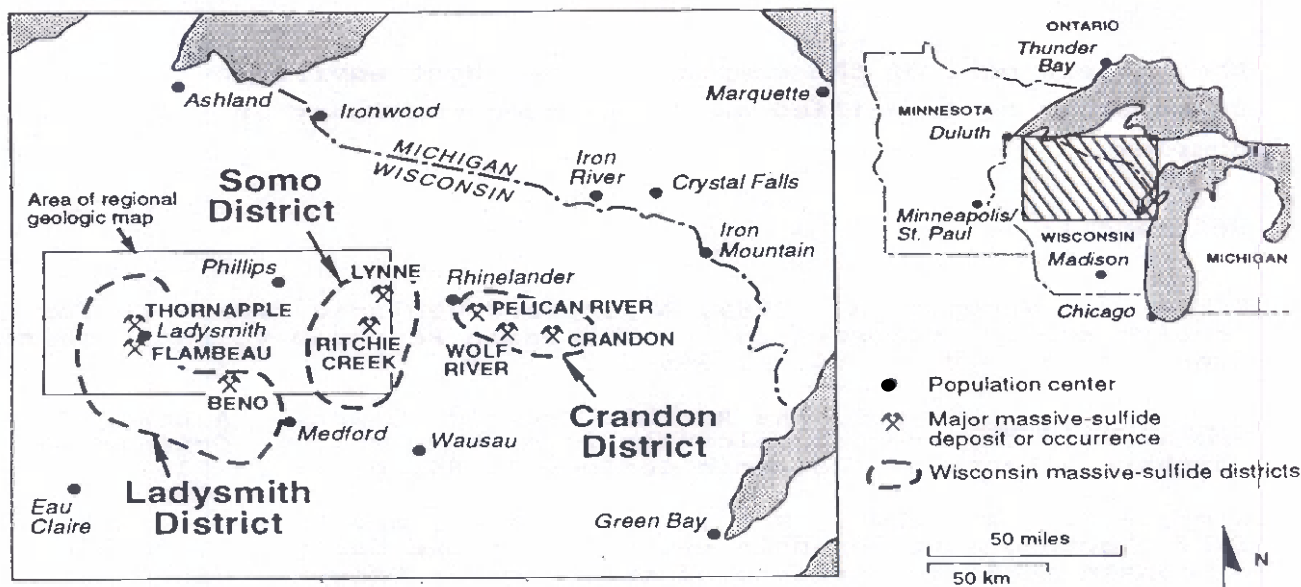
DeMatties, Theodore A., 1989, A proposed geologic framework for massive sulfide deposits in the Wisconsin Penokean volcanic belt: *Economic Geology*, v. 84, p. 946-952.

_____, 1960, The Ritchie Creek Main Zone: A Lower Proterozoic copper-gold volcanogenic massive sulfide deposit in northern Wisconsin: *Economic Geology* v. 85, p. 1908-1916.

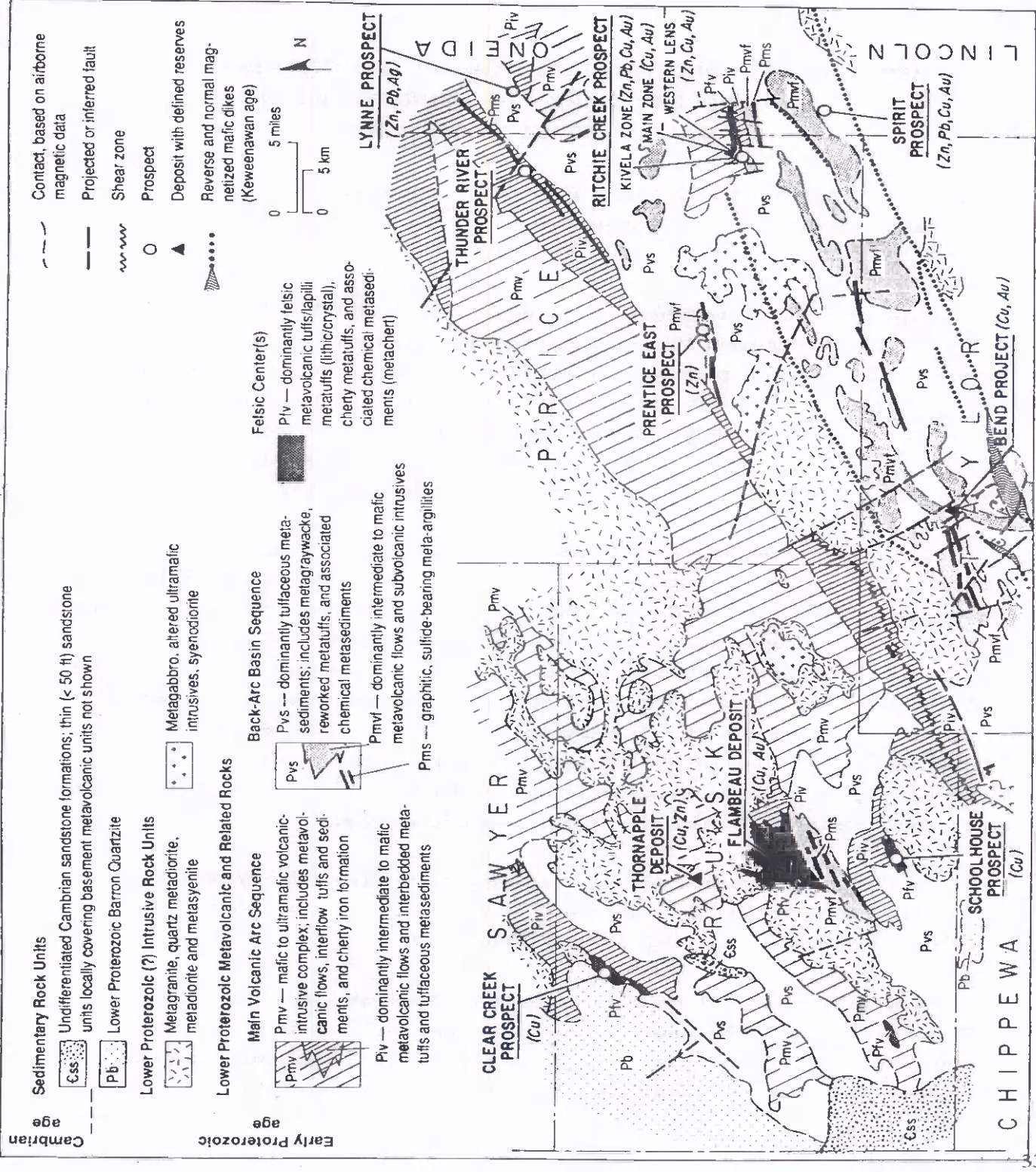
Sims, P.K., Van Schmus, W.R., Schulz, K.J., and Peterman, Z.E., 1989, Tectono-stratigraphic evolution of the Early Proterozoic Wisconsin magmatic terranes of the Penokean Orogen: *Canadian Journal Earth Science*, v. 26, p. 2145-2158.

Mudrey, M.G., Jr., Evans, T.J., Babcock, R.C., Cummings, M.L., Jr., Eisenbrey, E.H., and LaBerge, G.L., 1991, Case history of metallic mineral exploration in Wisconsin 1955-1990: *AIME, Case Histories of Mineral Discoveries*, v. 3, p. 117-132.

LaBerge, G.L., and Myers, P.E., 1984, Two Early Proterozoic successions in central Wisconsin and their tectonic significance: *Geological Society of America Bulletin*, v. 95, p. 246-253.



Index Map of Wisconsin Mineral Districts



Regional geologic map

BEND, A LOWER PROTEROZOIC, COPPER- AND GOLD-ENRICHED
VOLCANOGENIC MASSIVE-SULFIDE DEPOSIT IN
TAYLOR COUNTY, WISCONSIN

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Exploration work conducted between 1976 and 1991 by the Jump River Joint Venture (Wisconsin Mineral Resources Incorporated and Chevron USA Inc.) has identified a potentially economic copper-gold deposit within the Chequamegon National Forest in Taylor County, Wisconsin. Geophysical follow-up and evaluation by diamond drilling (over 30,000 feet in 25 holes) of a single-line AEM (INPUT) anomaly identified in 1977-78 resulted in the discovery of the Bend volcanogenic massive-sulfide deposit.

Geologically the project area lies within the west-central part of the Ladysmith-Rhineland Volcanic Complex, a member of the Lower Proterozoic Penokean volcanic belt of northern Wisconsin. The copper-gold mineralization occurs within an upright, steeply dipping, thick (up to 2000 feet), and relatively undisturbed felsic sequence dominated by rhyolite-rhyodacite flows, flow breccias, and fine to coarse pyroclastic tuffs and subordinate sedimentary rocks. At depth, this flow-pyroclastic section is intercalated with or intruded by a thick (nearly 1000 feet) series of silicic rhyolite flows which may be part of a larger domal structure. The felsic succession or center has developed along the flanks of a larger volcanic complex.

Ore reserves are hosted by an altered quartz crystal rhyolite tuff (quartz-sericite schist) and have been divided into a copper-rich hanging-wall horizon (HW) and a gold-rich footwall (FW) zone.

Two stacked stratiform massive (50-90%) to semimassive (greater than 30%) sulfide lenses (the upper lens and the middle lens) at or near the stratigraphic top of the quartz crystal tuff constitute the hanging-wall horizon. These lenses range from 5 to over 40 feet true thickness and

contain mostly fine- to very fine-grained, granular, pyrite with varying amounts of interstitial chalcopyrite $\pm$ tetrahedrite $\pm$ bornite $\pm$ gold tellurides. Gangue minerals include quartz, carbonate (calcite), and sericite. Petrographic analysis indicates that the majority of the pyrite grains contain very fine to submicroscopic inclusions of chalcopyrite and bornite. Individual beds within the lens may be fragment-bearing (altered and unaltered quartz-crystal tuff fragments) and exhibit vague to well-developed bedding/laminations. Sedimentary features such as graded bedding have been observed in drill core, suggesting a syngenetic origin. Both lenses extend to subcrop, and are overlain by about 120 feet of glacial moraine. Near the subcrop there is evidence of oxidation and supergene enrichment. Supergene minerals include chalcocite and bornite.

Each lens is partially underlain stratigraphically by a semiconformable, poorly developed stockwork-stringer or stringer like zone consisting of fine cross-cutting chalcopyrite veinlets and/or pyrite $\pm$ chalcopyrite anastomosing veinlets-veins and/or fine pyrite matrix supporting altered (silicified) medium to coarse-sized, subrounded-subangular quartz crystal tuff fragments. Locally wispy chalcopyrite stringers may overprint bedded massive sulfides. The stockwork stringer mineralization may be accompanied by weak to strong silicification and generally weak, wispy chlorite alteration. No well-developed alteration pipe has been recognized to date. Locally these zones may carry ore-grade gold values.

Both lenses are enveloped by a pyritic stockwork sulfide halo (up to 30% sulfides) which extends throughout the stratigraphic upper portions of the crystal tuff unit and along strike an undetermined distance. The stockwork halo consists of pyrite disseminations, bands, laminations, discontinuous cross-cutting and parallel (to foliation and bedding) veinlets and is associated with widespread pervasive sericitization. Stockwork-stringer mineralization developed stratigraphically below both lenses grades both vertically and laterally into the halo.

The footwall gold zone is comprised of at least two stratiform ore-grade (plus 0.1 oz/ton) gold assay subzones ranging from less than 10 feet to over

20 feet true thickness. One designated as the "tuck under" subzone is stratigraphically below the upper lens and hosted by stockwork sulfides. A second occurs within, above and along strike of a thin lower massive sulfide lens (or group of lenses) below the 600-foot elevation. Both assay subzones appear to have continuity along strike and down dip. Primary Cu, As, Bi, and Sb dispersion patterns developed in the stockwork halo indicate a geochemical continuity between the lower sulfide lens and the lower gold zone and suggest that it may widen at depth. Additional drilling is needed to fully delineate these gold subzones. Hypogene gold tellurides present include calaverite (AuTe), petzite (Ag_3AuTe_2), and krennerite (AuAgTe_4).

Widespread gold values greater than 0.01 oz/ton have been found throughout the stockwork sulfide halo. Higher values can form poorly developed strataform assay subzones of limited down dip or lateral extent.

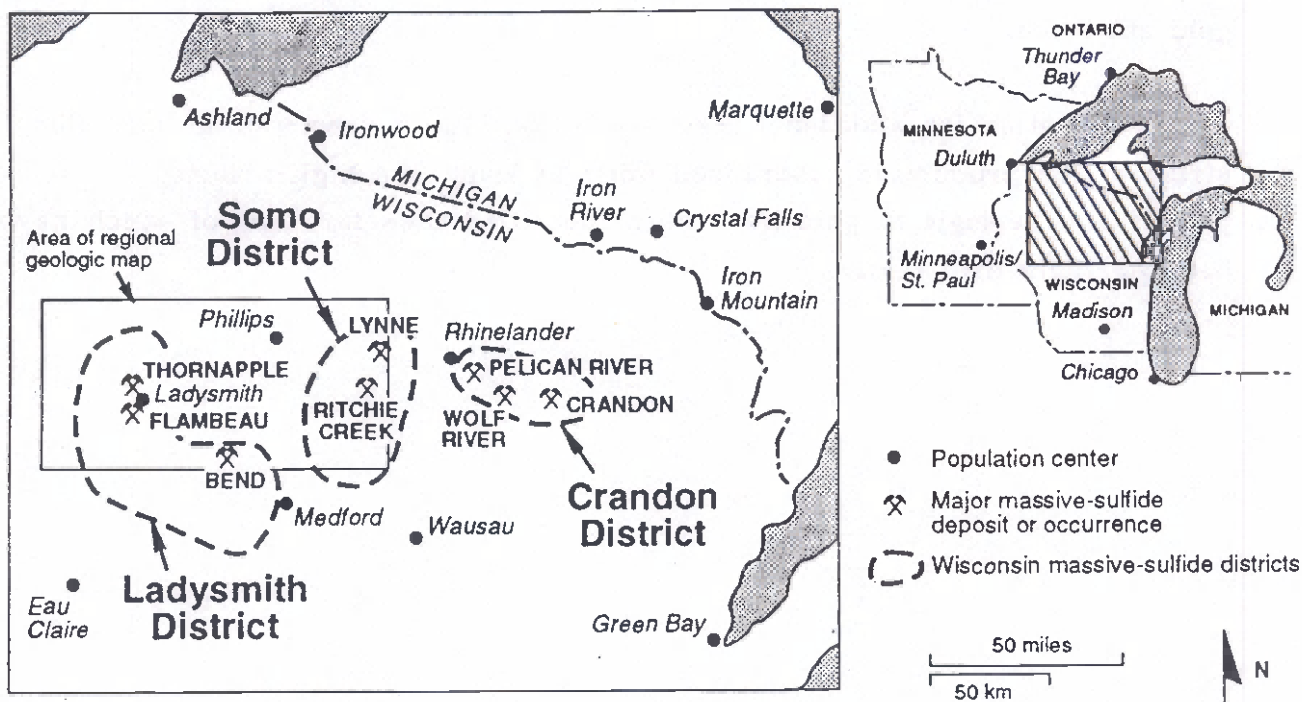
The geologic and geochemical data obtained thus far indicate that the Bend deposit exhibits characteristic hypogene copper-gold zoning patterns, i.e. development of copper-rich massive-sulfide lenses accompanied by several prominent parallel gold subzones. The isopach data indicate that the locus of the sulfide systems was both within and along a paleotopographic high developed by a thickening of the quartz crystal tuff unit. The massive-sulfide mineralization tends to be more fragment-bearing and disrupted near the top of the pile than toward its margins, where generally well-developed laminations and beds are evident. The sulfide system is believed to be plunging in two directions. This may be the result of paleotopographic control on sulfide deposition.

The presence of tetrahedrite explains the unusual geochemistry of the mineralization which includes anomalous concentrations of arsenic, bismuth, and antimony. Concentrations of tellurium are also anomalously high owing to the tellurides present.

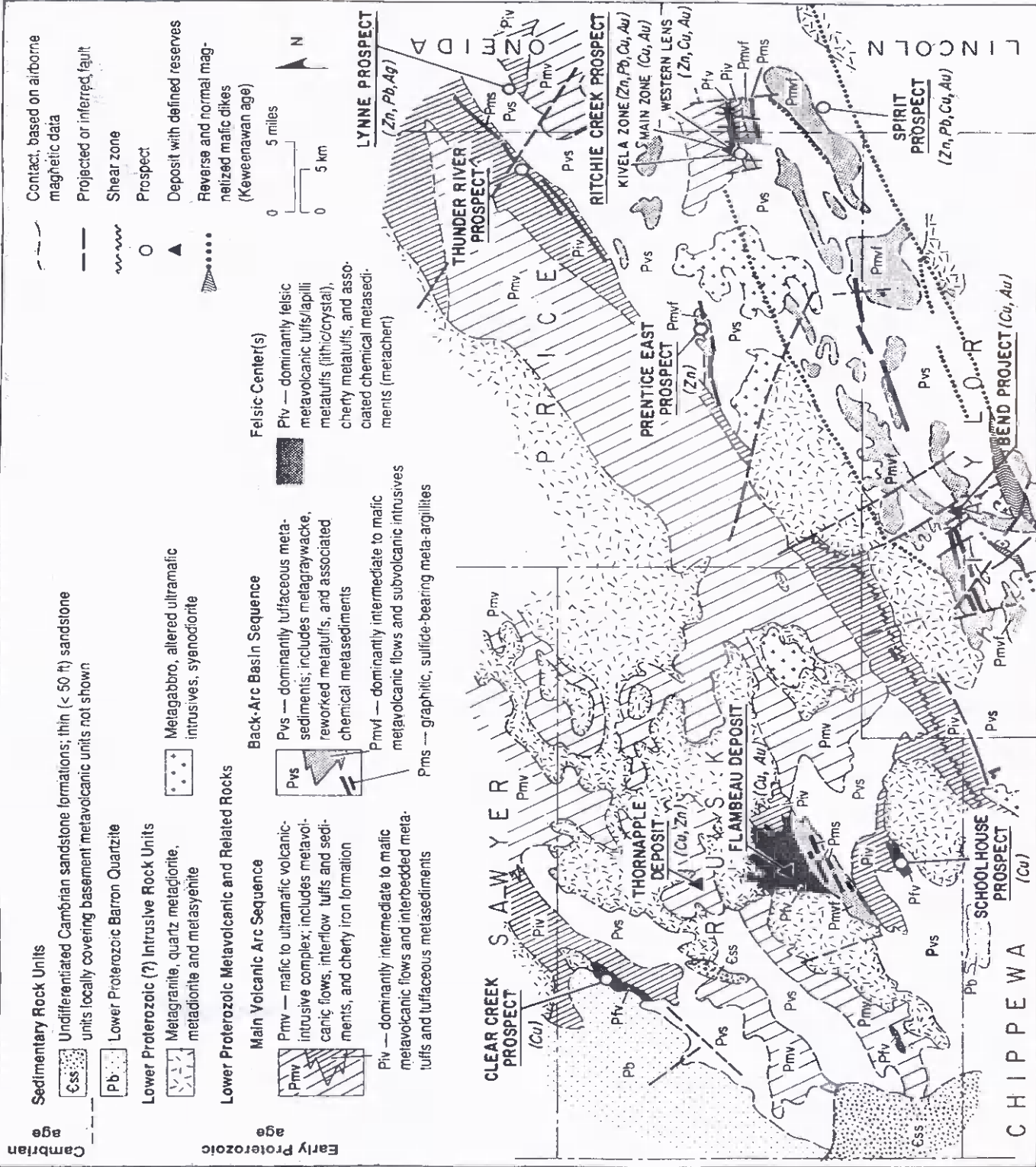
A geologic reserve base estimate as of March 1, 1991, of drill-indicated and -inferred reserves includes approximately 2.2 million short tons of 2.77% copper, 0.05 oz/ton gold, and 0.43 oz/ton silver in the stratigraphically

upper hanging-wall copper-rich horizon and an additional 1.5 million short tons of 0.14 oz/ton gold, 0.26% copper, and 0.11 oz/ton silver in the footwall gold subzones.

Exploration for additional reserves is continuing down-plunge and along strike of the productive mineralized unit; at least five high-priority geophysical-geologic targets have been identified thus far, two of which have been partially drill tested.



Index Map of Wisconsin Mineral Districts

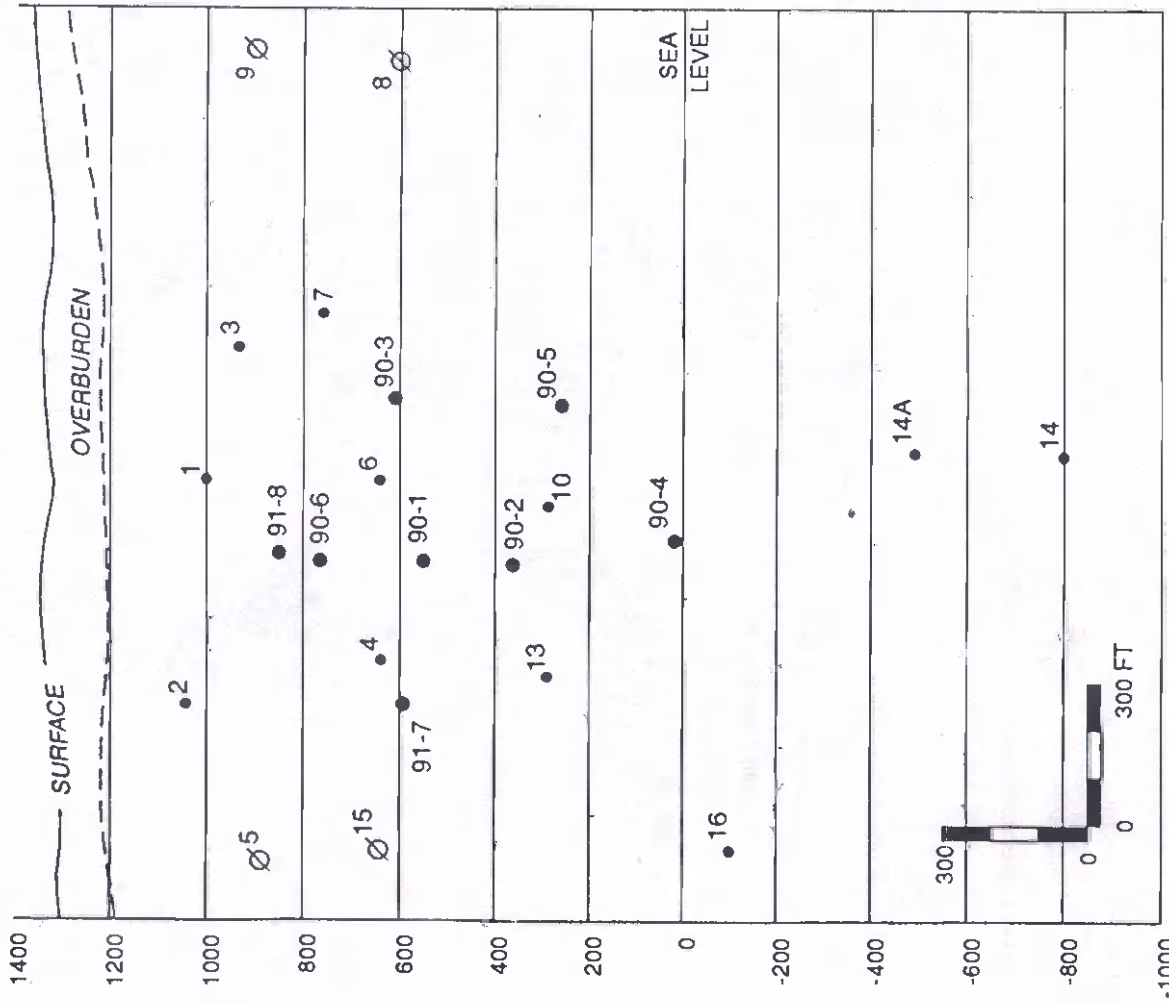


Regional geologic map

WSW

ENE

ELEV. ASL



○ = Weakly mineralized
 ● = 1986-1989 drillholes
 ○ = 1990-1991 drillholes

Assay Data

DDH#	True Thickness	% Cu	oz/ton Au	oz/ton Ag	
90-1	40.7' (14.1') (26.6)	2.66	0.076	0.61	HW
90-2	14.7' 12.3'	3.88	0.024	0.35	HW
90-3	21.8'	0.10	0.119	0.09	FW
90-4	7.4' 5.6' 5.2' 21.1'	2.22	0.023	0.29	HW
90-5	29.9' (7.1') 5.2' 6.1'	0.10	0.093	0.05	FW
90-6	69.5'	0.09	0.072	0.02	FW
90-7	5.1' 16.5' 11.9'	0.08	0.476	0.22	FW
90-8	61.4'	0.08	0.056	0.02	FW
90-9	29.9' (7.1') 5.2' 6.1'	0.11	0.041	0.03	FW
90-10	69.5'	0.13	0.058	0.05	FW
90-11	5.1' 16.5' 11.9'	0.01	0.052	0.01	FW
90-12	61.4'	0.02	0.067	0.01	FW
90-13	69.5'	2.46	0.038	0.38	HW
90-14	5.1' 16.5' 11.9'	1.28	0.041	1.12	HW
90-15	61.4'	0.20	0.085	0.02	FW
90-16	5.7'	0.04	0.055	0.02	FW
90-17	61.4'	1.87	0.089 (cut)	0.35	HW
90-18	5.7'	0.10	0.139	0.10	FW

HW - Hanging wall zone FW - Footwall zone

MARCH 1991

Longitudinal Projection of Mineralization, Bend Project

Taylor County, Wisconsin

GEOLOGY AND PETROGRAPHY OF THE AMNICON PLUTON, DOUGLAS COUNTY, WISCONSIN

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The small, sill-like Amnicon intrusion located southeast of Superior, (Douglas County), Wisconsin, identified by Dickas and others (1969), and Mengel (1970), has now been mapped in detail. The Amnicon Pluton exceeds 6 square km. in outcrop area and is named for exposures along the bank of the Amnicon River in sec. 32, T. 48 N., R. 12 W. It is poorly exposed in sec. 31 and 32, T. 48 N., R. 12 W., and sec. 5 and 6, T. 47 N., R. 12 W. (Figure 1). No contacts were observed, and the outcrop extent coincides approximately with the mapped magnetic signature (Dickas and others, 1969). Field relations indicate intrusive contact with surrounding Chengwatana basalt and interbedded volcanoclastic units is well constrained to the north, and moderately constrained to the east and west. The southern margin appears to be a chilled contact.

Two phases are evident. A troctolite occupies the northwestern part of the body and granophyre the southeastern part. Because the contact between these phases is approximately parallel to the northeast regional trend of the enclosing Chengwatana Volcanics, we interpret the Amnicon Pluton to be a sill. The spatial relationship of the granophyre to troctolite suggests the granophyre is the youngest phase. The troctolite consists of 10% olivine (0.9 mm in diameter) and 70% plagioclase (An₆₅, 0.3 to 0.9 mm in size) set in a subophitic groundmass of 20% clinopyroxene. Compositional layering within the troctolite is weak at best. Opaque oxides are marked by well developed reaction rims. The granophyre consists of 0.45 mm long by 0.02 mm wide plagioclase set into a sericitized, calcitized groundmass. Blocky opaque oxides amount to 2% by volume. Quartz is poikilitic. Chemical analyses of the Amnicon Pluton are given in Table 1.

Line diagram interpretation of the upper 2.5 sec. TWT (two-way travel time, 1 sec. equals approximately 3,000 m) of a migrated, reflection seismic profile acquired by Petty-Ray Geophysical Division of Geosource Inc. (presently Halliburton Services) along Highway 53 in 1984 and across the known exposures of the Amnicon Pluton is shown in Figure 2 (see Figure 1 for location). Our interpretation suggests a near-surface sill-like geometry to a depth of 1 sec. TWT, increasing in thickness at greater depths. Southeastern contacts are clearly defined by lateral termination of reflections from the beds in the Chengwatana Volcanics while Douglas Fault-related contact is moderately identified to the northwest by lateral Bayfield-Oronto (?) reflection terminations. Near surface contact between the Amnicon Pluton and surrounding rock units is further defined by characteristics of a gravity and magnetic profile taken in conjunction with the seismic profile. This igneous body appears to dip at a high angle subparallel to the 45 degree southeast dip of the Douglas Fault as measured at Amnicon Falls State Park, suggesting the "Amnicon" magma employed the Douglas Fault rift detachment plane as a preferred avenue for emplacement.

The Amnicon intrusion is chemically, structurally, and petrographically similar to the other major Keweenaw intrusive suites associated with the Midcontinent Rift in the western Lake Superior region, the Duluth Igneous Suite to the north and the Mellen Intrusive Suite to the east (Table 1), and probably represents a minor, high-level differentiated gabbroic body.

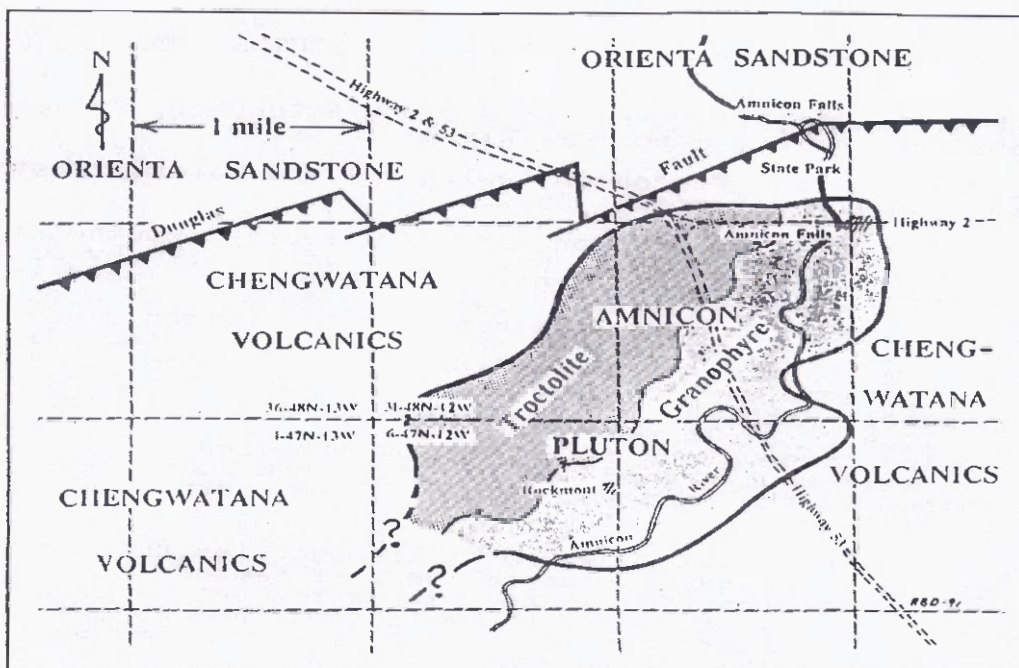


Figure 1. Areal distribution of the Amnicon Pluton and its relation to regional, Middle Proterozoic (Keweenaw) geology of the Midcontinent Rift System within Douglas County, Wisconsin.

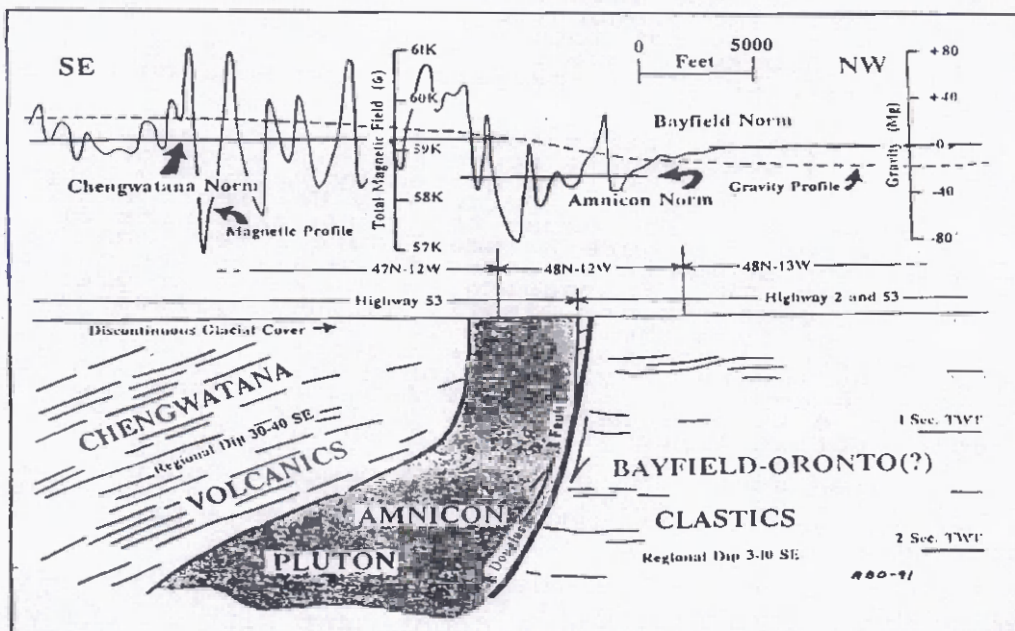


Figure 2. Line diagram interpretation of the upper two and one-half seconds of reflection seismology, magnetics, and gravity as collected along highways 2-53 and 53, Douglas County, Wisconsin. Display presented here courtesy of Halliburton Geophysical Services, Inc., Texas.

Oxide (%)	Amnicon		Mellen (1)	Duluth (2)
	Troctolite	Granophyre (3)		
SiO ₂	50.4	69.8-71.8	49.7	47.7
TiO ₂	1.8	0.3- 0.6	1.4	1.3
Al ₂ O ₃	18.3	11.7-12.1	18.4	18.4
FeO	9.9	4.3- 5.1	10.5	10.6
MnO	0.2	0.1- 0.1	0.1	0.2
MgO	5.1	0.3- 0.8	6.1	5.3
CaO	9.9	2.0- 1.7	9.9	11.2
Na ₂ O	3.2	3.2- 3.5	2.9	2.4
K ₂ O	0.6	4.1- 4.1	0.6	0.5
P ₂ O ₅	0.4	0.1-<0.1	0.2	0.2
LOI	0.8	1.9- 0.9	---	---
Totals	100.6	97.8-100.7	99.8	97.8

- (1) Possible parent magma composition of Potato River Intrusion (Eastern Mellen Intrusive Suite) (Klewin, 1987, p. 152)
- (2) Possible parent magma composition of North Shore Volcanic Group (Green, 1972)
- (3) Percentage range of two analyses of granophyre phase

Table 1. Chemical analyses of the two petrographic phases within the Amnicon Pluton, with comparison of the Amnicon troctolite phase with similar phases from the Mellen and Duluth intrusives.

References:

Dickas, A. B. et al., 1969, Relationships of regional magnetics to the bedrock geology of the South Range Quadrangle, Douglas County, Wisconsin: Abstracts, 15th Inst. Lake Superior Geology, p. 12-14.

Green, J. C., 1972, North Shore Volcanic Group, in Sims, P. K. and Morey, G. B., (eds), Geology of Minnesota: A centennial volume (G. M. Schwartz Volume), Minnesota Geological Survey, p. 294-332.

Klewin, K. W., 1987, The petrology and geochemistry of the Keweenaw Potato River Intrusion, northern Wisconsin: unpublished Ph. D. dissertation, Northern Illinois University, 357 p.

Mengel, J. T., 1970, Geology of the western Lake Superior region, privately printed, 86 p.

Tabet, D. E., and Mangham, J. R., 1978, The geology of the eastern Mellen Intrusive Complex, Wisconsin: Geoscience Wisconsin, v. 3, p. 1-19.

Weiblen, P. W., 1982, Keweenaw intrusive igneous rocks, in R. J. Wold and W. J. Hinze (eds): Geology and tectonics of the Lake Superior Basin, Geol. Soc. America Memoir 156, p. 57-82.

REGULATING METALLIC MINERAL DEVELOPMENT IN WISCONSIN

Thomas J. Evans, Wisconsin Geological and Natural History Survey

Despite the significant potential for metallic mineral deposits in the Ladysmith/Rhineland volcanic complex of northern Wisconsin, only one mining project has received permits for actual mineral development. In part, the regulatory framework for metallic mining has been responsible for the slow pace of mine development.

The statutes and administrative rules governing metallic mineral development in Wisconsin form a comprehensive, broad-based regulatory framework. In addition to extensive environmental regulations focusing on groundwater, surface water, air, water-supply wells, and wastewater discharge activities, Wisconsin has adopted a net proceeds tax on the occupation of metalliferous mineral mining.

The regulations affecting metallic mining in Wisconsin include a thorough assessment of environmental impacts and, together with the extensive permitting requirements, result in a lengthy process from mineral discovery to eventual mine start-up. However, the process does provide a mechanism that will lead to positive decisions on the necessary permits, as long as the environmental standards can be addressed.

The net proceeds tax provides a reasonable tax basis for mineral development. This tax, often misunderstood or mischaracterized by the mining industry in the early years after its adoption in 1977, was modified in 1981 to clarify and expand certain allowable deductions and to reduce the overall tax rate so that it was more closely tied to the profitability of mining ventures. Although the tax is an added burden or "cost of doing business" in Wisconsin, it does not have a significant impact on the overall potential for mining in Wisconsin.

The modified net proceeds tax, a "workable" mine-permitting process, and recent decisions that favor mineral leasing create a positive climate for mining; however, the small but vociferous anti-mining activity and recent legislation that would severely limit mining in the state do much to obscure that positive climate. It is important to remember the "upside" when you are up to your ears in the "downside".

GEOLOGY OF PLATINUM GROUP ELEMENT - ENRICHED HORIZONS
WITHIN THE DUNKA ROAD COPPER-NICKEL PROSPECT
ST. LOUIS COUNTY, MINNESOTA

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The Dunka Road Cu-Ni prospect is located within what is informally known as the Partridge River intrusion (T. 60 W., R. 13 W.), which is part of the Duluth Complex, 1.1 b.y. (Keweenawan) in age (Figure 1). Seven major lithologic units, along with several internal ultramafic subunits, have been identified and are correlatable over the deposit. The ultramafic subunits (layers of picrite to dunite), exhibit relative uniform thicknesses and are present at the same relative position within the major lithologic units. The major lithologic units are the same as delineated by Severson and Hauck (1990), and upward from the basal contact are (Figure 2): Unit I, a fine- to coarse-grained sulfide-bearing anorthositic troctolite to pyroxene troctolite (450 ft. thick) with associated ultramafic layers I(a), I(b), and I(c); Unit II, a medium- to coarse-grained troctolite to pyroxene troctolite (200 ft. thick) with a basal ultramafic layer II(a); Unit III, a fine-grained, mottled textured troctolitic anorthosite to anorthositic troctolite (200 ft. thick); Unit IV, a coarse-grained anorthositic troctolite to pyroxene troctolite (400 ft. thick); Unit V, a coarse-grained anorthositic troctolite (300 ft. thick); Unit VI, a fine- to coarse-grained troctolitic anorthosite to troctolite (400 ft. thick) with basal ultramafic layer VI(a); and Unit VII, a coarse-grained troctolitic anorthosite to anorthositic troctolite (400+ ft. thick) with basal ultramafic layer VII(a).

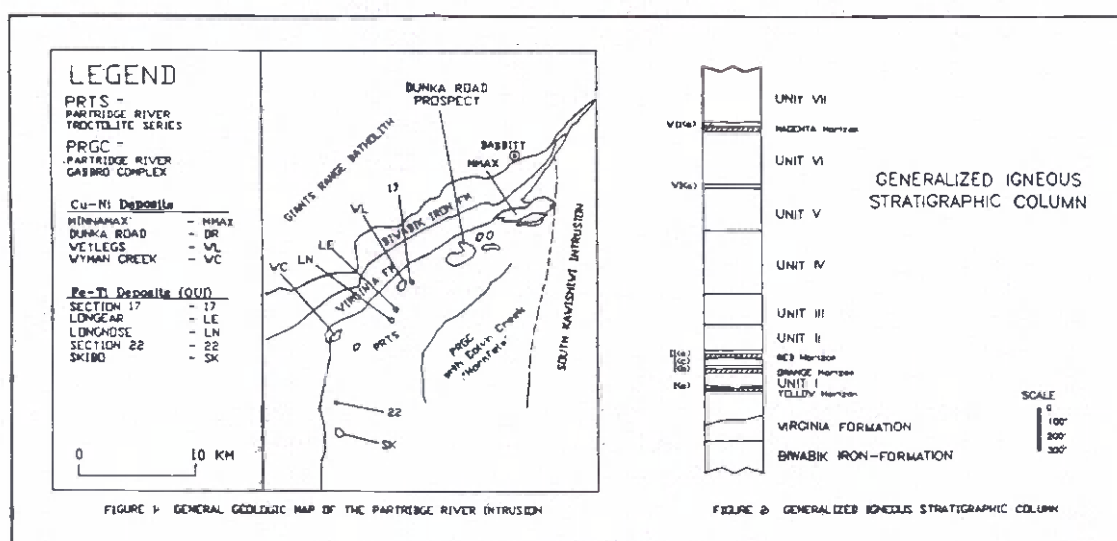
Most sulfide mineralization occurs within Unit I. The sulfide mineralization is both interstitial and widespread, but variable in modal percentage (rare to 5%), continuity, and thickness (few inches to tens of feet). Sulfide mineralization is generally related with proximity to: hornfels inclusions, basal contact with the footwall Virginia Formation, and some of the internal ultramafic layers within Unit I. Primary sulfide mineralization includes chalcopyrite, pyrrhotite, pentlandite and cubanite. Minor amounts of bornite, native copper, talnakhite and mackinawite or valleriite have also been identified in preliminary petrographic observations. Pt+Pd values range from 100 to >2400 ppb over 10 foot intervals, and these occur as isolated values or along stratigraphic horizons in the upper 3/4 of Unit I.

Several Cu/PGE-enriched horizons have been identified, and occur laterally throughout the prospect. The most continuous horizon, (RED Horizon) is found directly beneath ultramafic layer II(a), within the uppermost portion of Unit I. This horizon ranges from 10 to 30 feet thick and contains average values of 0.65% Cu and 1200 ppb Pt+Pd. Two other horizons, (ORANGE Horizon and YELLOW Horizon) occur roughly at 100 and 200 feet beneath Red Horizon, respectively. These are less continuous horizons that range from 10 to 50 feet thick and contain average values of 0.70% Cu and 1000 ppb Pt+Pd. Only one PGE-enriched horizon has been identified outside of Unit I. It occurs in Unit VI (MAGENTA Horizon), directly beneath ultramafic layer VII(a). Although it has been identified in only six drill holes to date, it ranges from 10 to 30 feet thick and contains average values of 0.90% Cu and 1875 ppb Pt+Pd.

The predominant host rock for these Cu/PGE-enriched horizons is coarse-grained anorthositic troctolite, which may exhibit some subtle fracturing accompanied with minor alteration. The alteration assemblage within these mineralized zones is serpentine, uraltite and saussurite. This type of alteration assemblage has also been observed throughout the entire prospect, but is not always associated with mineralization. Although the majority of sulfide mineralization is believed to be primary, mineralized zones that are intersected by fractured/alterated zones can contain secondary sulfides and textures, suggesting local enrichment. The majority of the sulfide itself is coarse-grained (5 mm) and commonly rimmed by secondary red-brown biotite. Ilmenite occurs in two habits within these zones, as euhedral to subhedral laths throughout the host rock, and as "bleb-like" black shiny droplets within the sulfides. This second ilmenite habit has only been identified in sulfide zones that are enriched in Pd and/or Pt.

References:

- Morton, P., and Hauck, S. A., 1987, PGE, Au and Ag contents of Cu-Ni sulfides found at the base of the Duluth Complex, northeastern Minnesota: Natural Resources Research Institute, Technical Report NRRI/GMIN-TR-87-04, 85 pp.
- Morton, P., and Hauck, S. A., 1989, Precious metals in the copper-nickel deposits of the Duluth Complex: Minn. Geol. Survey, Inf. Circ. 30, pp. 47-48.
- Severson, M. J., and Hauck, S. A., 1990, Geology, geochemistry, and stratigraphy of a portion of the Partridge River Intrusion, northeastern Minnesota: Natural Resources Research Institute, Technical Report, NRRI/GMIN-TR-89-11, Duluth, Minnesota, 240 pp.



DRIFT PEBBLE LITHOLOGY OF THE TOMAHAWK ROAD AREA, LAKE COUNTY, MINNESOTA, USED TO HELP INFER LOCAL BEDROCK

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Abstract

In 1989 a multi-media, regional, geochemical orientation and reconnaissance survey was completed for a portion of Lake County, Minnesota. The results of this survey suggest that three anomalous localities exist across the project area. It was also concluded that the geochemical survey reflects bedrock lithologies, despite variable glacial overburden thickness of several deposit types and a complex depositional history, (Buchheit et al., 1989, p. 1). These results were related to the geology as mapped by Green on the 1:250,000 scale, "Geologic Map of Minnesota, Two Harbors Sheet", (1982) but the complex pattern of geochemical results made obvious the need for a more detailed geologic map to assess this relationship.

Traditional geologic maps are a reflection of the quantity and quality of available geologic information, which did not provide the needed detail. Improved quality of geophysical surveys and sophisticated computer enhancement techniques now provide the means to generate inferred geologic maps. For accuracy and detail these maps require high resolution aeromagnetic and regional gravity surveys, provided in Minnesota by an aeromagnetic survey funded by the Legislative Commission on Minnesota Resources (LCMR) and a gravity survey by the Minnesota Geologic Survey (MGS). Geologic interpretations made from remote measurements of physical properties are known as pseudo-geologic maps.

As a pilot test of the practicality of these maps, the Department of Natural Resources (DNR) contracted with private consultants to interpret geophysical data and make maps in two areas. One of the areas selected was a four township block in the McDougal Lakes Area of Lake County, in the interior of the Duluth Complex, a Proterozoic layered mafic intrusive complex. This area was mapped by Robert J. Ferderer, Eagan, Minnesota. Ferderer's pseudo-geologic map is much more detailed than its predecessor The Two Harbors geologic map. Lithologic units and structural features are confirmed by verification procedures wherever tested. In addition to lithologic units and structural features this map has three dimensional aspects shown by depth to magnetic source calculations and forward modeling profiles. A portion of this map in the pebble count area is shown on Plate 3.

In this area glacial cover is 0 to 65 feet deep, and there are some outcrops, but prior to this program there were only three drill holes. To verify the pseudo-geologic map it was tested with: 1) Six drill holes, with lithologic logging using assays and thin section studies; 2) Geophysical measurements on the core; 3) Ground geophysical traverses over selected features; and 4) Pebble counts of glacial till and outcrop studies that relate lithologic observations to geophysical parameters. The pebble count, thin section, outcrop studies, and drill core logging were done by, or under the direction of, John C. Green (University of Minnesota - Duluth).

The pebble counting technique used by Green and Venzke (1990) was to determine if glacial drift pebble composition can be used to determine the lithology of the underlying bedrock in drift-covered areas. A strip of sections was chosen along the Tomahawk Road where, with additional outcrop mapping and drill hole logging, an improved geologic map could be made to evaluate the results of the pebble counts and the pseudo-geologic map. Although some contacts are poorly constrained due to gaps in outcrop and drill hole coverage. Bedrock units of anorthosite, olivine gabbro and troctolite of the Bald Eagle Intrusion, and one or two troctolite units were mapped. Based on counts of the 50 largest pebbles in each sample, four lithologic drift units were mapped: 1) Troctolitic; 2) Transition Zone; 3) Anorthositic; and 4) Mixed Volcanic (Plate 5).

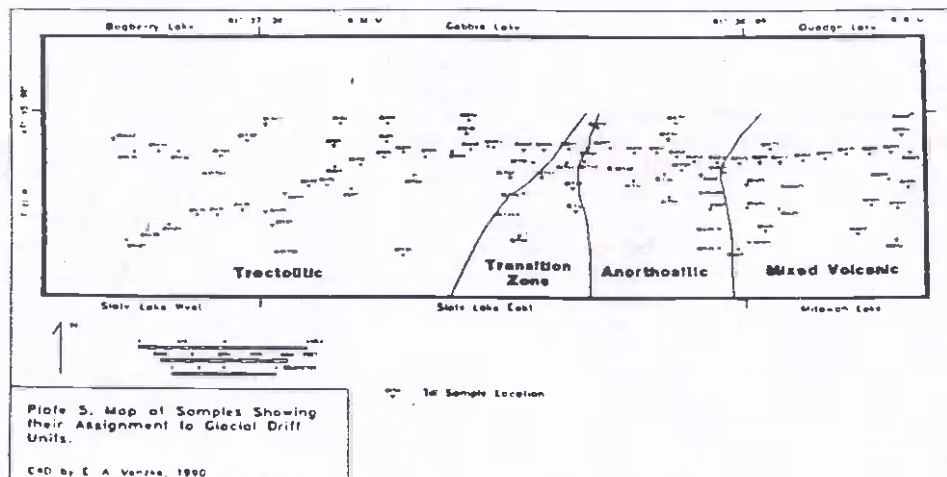
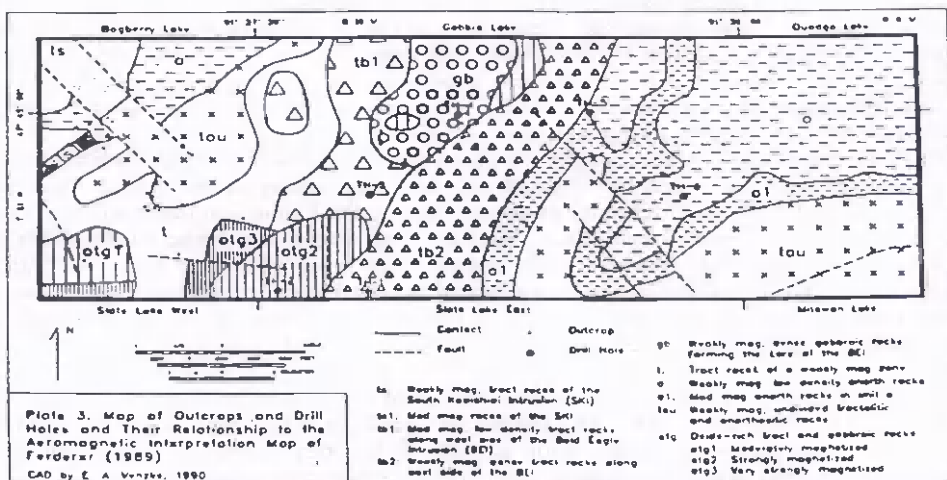
In general, the most abundant pebble type in these samples corresponds to the underlying bedrock type, suggesting that this technique can be useful for "remotely sensing" bedrock types in covered areas. However, in the eastern 1/4 of the area the drift is dominated by lithologies (Archean, Animikie, Keweenawen lavas, granophyre) that have been transported for long distances (several 10's of km) from the E, ENE, or ESE. This must have been carried by the Superior Lobe and is clearly not basal till (directly overlying bedrock). Elsewhere in the study area, ice transport has produced some gradations or transition zones in the drift pebble assemblages, compared to the bedrock contacts. Also, since glacial transport in the Rainy Lobe (dominant here) was primarily roughly parallel to the main bedrock contact (anorthosite vs troctolite), the pebble assemblage at any sample site may have come largely from a few km up-ice. Thus the technique will be most successful when the drift is

relatively thin and its stratigraphy is known well enough to exclude the existence of an upper drift sheet that is not in contact with local bedrock, and where rock boundaries are at large angles to ice transport direction, (Green and Venzke 1990).

Comparing geochemical results with Ferderer's map there is a correlative relationship between the west contact area of his *tb2* unit and high geochemical assays. This unit is similar in areal extent to the *dg* unit on the Two Harbors Sheet. Anomalous geochemical values also correlate with Ferderer's fault zones.

Buchheit, R.L., Malmquist, K.L. and Niebuhr, J.R., 1989, "Glacial Drift Geochemistry for Strategic Minerals; Duluth Complex, Lake County, Minnesota", Minnesota Dept. of Natural Resources, Division of Minerals, Report 262.

Green J.C. and Venzke, E.A., 1990, "Drift Pebble Lithology of the Tomahawk Road Area, Lake County, Minnesota: Can it be Used to Infer Local Bedrock?", Minnesota Dept. of Natural Resources, Division of Minerals, part of Report 290.



GROUND GEOPHYSICAL SURVEYS LEADING TO THE BEND COPPER-GOLD DISCOVERY

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SUMMARY

The initial ground geophysical surveys were intended to follow up a 1977 INPUT airborne electromagnetic (AEM) anomaly located in the Chequamegon National Forest in Taylor County, Wisconsin. The anomaly was delineated on only one flight line. The ground geophysics consisted of horizontal-loop frequency electromagnetics (HLEM) and total-field magnetics profiling. Five north-south survey lines, spaced 400 feet apart, were placed over the anomaly. A strong nonmagnetic conductor was encountered on two of the central lines, suggesting the occurrence of a steeply dipping massive sulfide lens with short strike length. Subsequent drilling, which began with two cored holes drilled on each of the anomalous HLEM survey lines, verified the conductive source as being due to massive chalcopyrite mineralization. Assays of core samples indicated the presence of ore-grade gold as well. The importance of ground geophysical follow-up over single-line or poorly defined AEM anomalies cannot be overestimated.

INTRODUCTION

North-central Wisconsin has been a focal point for massive-sulfide exploration since Kennecott Copper initiated a large exploration program in the late 1950s. They were originally led to the area because of favorable outcrops (primarily in Rusk County), new volcanogenic models, and improved AEM systems. The AEM surveys in particular were responsible for the initial discoveries of the economic Flambeau deposit and, to a major extent, the subeconomic Thornapple deposit, both located near Ladysmith. Further to the east, AEM exploration programs by the Central Wisconsin Joint Venture (Getty Minerals and Ernest K. Lehmann & Associates), Noranda, and Exxon led to the discoveries at Ritchie Creek, Pelican River, and Crandon in the mid- to late-1970s. More recently, an exploration program funded by the Jump River Joint Venture (Chevron USA and Wisconsin Mineral Resources), although flown much earlier by the Getty-Lehmann joint venture (CWJV), led to the

geophysical discovery of the Bend massive sulfide in 1986. In 1990, Noranda announced its discovery of the zinc-rich Lynne deposit, also originally delineated with AEM. This paper will discuss the sequence of geophysical events that ultimately led to the Bend copper-gold discovery.

DISCUSSION

The Bend deposit is located in the Chequamegon National Forest in Taylor County, about 12 miles northwest of Medford. The airborne anomaly may have been recognized at least as early as 1974 when National Lead Industries conducted an AEM (INPUT) survey over the area. However, no ground follow-up was done, probably because of the poor quality of the anomaly. At about the same time, Kerr-McGee Corporation also flew an AEM survey over the area but, again, did not perform ground geophysics.

Later, in 1977, adjacent surveys were flown simultaneously by AMAX and CWJV. Both surveys detected the Bend massive sulfide. AMAX obtained prospecting permits in the area but, because of difficulties in securing a land position, did not pursue exploration efforts and left the area in 1978. The Getty-Lehmann joint venture dissolved in 1983 when Getty ceased mineral exploration operations. Chevron Resources, which also had an interest in the joint venture, became the major partner and continued the exploration work through a new joint venture (JRJV). Its ground geophysical program began with HLEM and ground magnetics surveys in February, 1986.

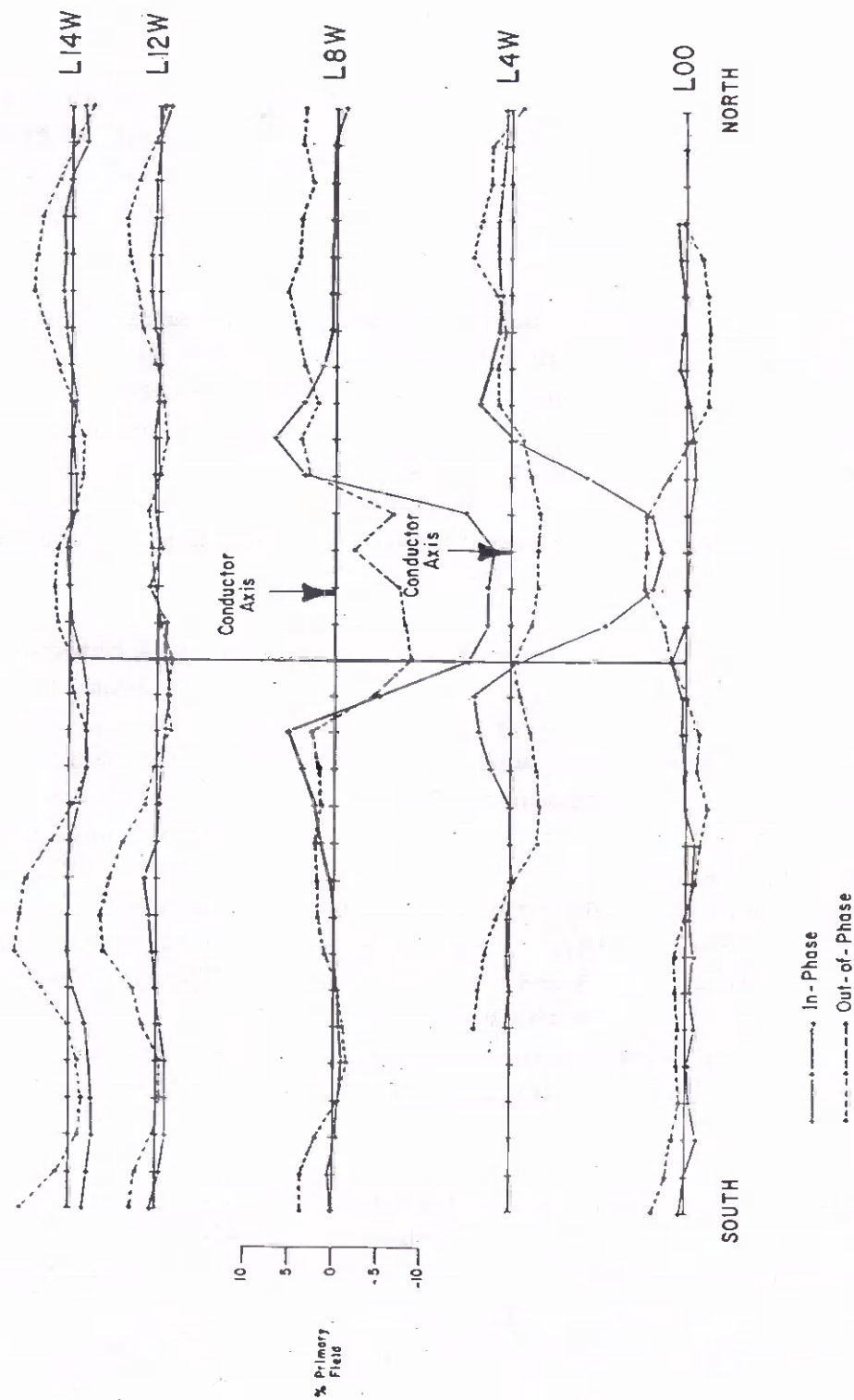
Five north-south geophysical lines, each approximately 5000 feet long, were positioned over the AEM anomaly. Ground magnetics were run with a Geometrics proton precession magnetometer at 50- and 100-foot intervals. No residual anomaly could be discerned in the vicinity of the AEM response.

MaxMin II HLEM profiling was also undertaken. A constant 600-foot separation was maintained between the transmitter coil and receiver coil, resulting in a penetration depth of about 300-400 feet. In-phase and quadrature components of the vertical secondary field were recorded for three frequencies at 100-foot intervals. The 444 Hertz data are shown in profile form in Figure 1. A strong bedrock conductor (up to 93 mhos) was defined on lines 4W and 8W and formed the basis for the initial drilling. The first

FIGURE 1

BEND MAXMIN PROFILES - 444 HZ

HLEM Coll Separation = 600 Feet



two holes, drilled in October 1986, were collared on lines 4W and 8W and intersected a thick massive-sulfide conductor, now known as the Bend deposit. To date, 25 cored holes have delineated 3.7 million tons of copper-gold mineralization in two zones. Depending on permit requirements, mining operations could begin as early as 1995.

In order to investigate the possibility of the occurrence of deep mineralization along strike, a large-loop time-domain EM-37 survey was performed. Large-loop electromagnetic systems are often used for exploring deep ore deposits. At Bend, several additional survey lines were added, east and west of the original five-line grid, and surveyed with the EM-37 system. The data indicate deep conductors both east and west of the Bend deposit, very nearly on strike with the known mineralization. At this time drilling has not confirmed the results of the EM-37 survey.

It is important to note that the Bend AEM anomaly was detected by a single flight line during the 1977 survey. The nominal line spacing used during the survey was 1/4 mile (1320 feet). Considering that the high-amplitude HLEM anomaly has a short strike length at the subcrop (400+ feet), it is fortunate that the deposit was detected at all. If the flight line had been displaced slightly to the east or west, the response would have been greatly diminished, reducing its attractiveness as an exploration target. To complicate matters, several other formational conductors are located to the north, northeast, and southwest. One of these was drilled shortly after the initial discovery of Bend and found to be conductive graphitic argillite. Several holes, too shallow to test the weak EM-37 responses along strike with the Bend conductor, were drilled and found to contain little or no sulfide mineralization. However, the geologic section containing the host felsic tuff unit persists.

Geophysical work is continuing along the Bend volcanic trend in an attempt to locate sister orebodies. Recent drilling southwest of Bend has shown that the felsic tuff host rock does strike for several thousand feet at least. Ground geophysical work to the northeast suggests similar trends in that area. Small volcanogenic massive-sulfide deposits such as Bend usually occur in clusters and continued exploration will undoubtedly result in additional discoveries.

CONCLUSION

In north-central Wisconsin, it is likely that most massive-sulfide deposits will be small, averaging only a few million tons and will be geophysically expressed as short-strike-length anomalies. This may be a result of (1) primary sulfide deposition, (2) structural complications, (3) conductive overburden, (4) depth of burial, and/or (5) flight-line orientation and location. Therefore, most AEM surveys should be flown with 1/8-mile (660 feet) spacing. All single-line anomalies and subtle anomalies should be investigated with appropriate ground techniques, if possible.

Over the years several AEM exploration programs were undertaken in or around the Bend area by different companies. For various reasons the Bend AEM anomaly was not investigated, not recognized for its importance, not well defined or, perhaps, not detected at all. Whatever the reason, the discovery illustrates the need for persistence and thoroughness in exploration, even if an area has been looked at before. Weak or poorly defined AEM anomalies or anomalies without direct magnetic support should always be considered for further evaluation if geologic conditions warrant.

GEOLOGY OF THE MERIDIAN AGGREGATES QUARRY AND THE SURROUNDING AREA, ST. CLOUD, MINNESOTA: A STUDY OF THE BEDROCK INFLUENCES ON THE PRE-LATE CRETACEOUS WEATHERING PROFILE.

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The Meridian Aggregates Quarry in St. Cloud, Minnesota contains a complex group of metamorphic and igneous rocks. Residual clays overlie the bedrock in some areas of the quarry. The focus of the study is to relate the composition and physical characteristics of the parent rocks to the overlying residual clay deposits. The quarry has been mapped at a scale of 1:1200, in order to give sufficient control of the geology and structural characteristics. This information has been linked with information from regional studies to better understand the controls on clay distribution in the St. Cloud area.

Because the composition of the parent rock is a critical factor in the composition of the clays that form during weathering, detailed mapping of the rock types in the quarry was critical. Five major rock types have been mapped: 1) a dark metamorphic rock type, 2) gray reformatory granite, 3) St. Cloud Granite, 4) mafic dikes, and 5) a porphyritic rhyolite dike. The dominate rock type in the quarry is the dark gray metamorphic. All of the rock types can be found in the western quarry wall where residual clays have developed on them.

The most important physical characteristic related to the formation of the residual clays is the presence of faults throughout the quarry. Many of the residual clay occurrences in the St. Cloud area are found in linear bedrock lows. Work in the Meridian Aggregates Quarry shows that the residual clays are found in bedrock lows along fault traces. This conclusion is based on bedrock and drill hole information from the quarry. In the quarry area, glacial deposits rest directly on bedrock or the residuum. Any overlying residual clays that may have developed in other areas of the quarry, would have been removed prior to or during glaciation, leaving pockets of residuum in bedrock lows. Three major structural features in the quarry were outlined by mapping: 1) an east-west trending fault zone on the north wall of the quarry; 2) a central, northeast trending fault zone; and 3) a western, northwest trending fault zone. The deepest clay formation in the quarry is associated the northwest fault zone. Drill hole information, provided by Meridian Aggregates outlines the extension of this zone outside the active quarry area. In addition, the drill hole information locates the deepest clay development near where the northwest fault zone an the east-west fault zone are thought to intersect. Other northwestern trending, residual clay filled bedrock lows, have been identified to the northeast and southwest, which correspond with linear features visible on high altitude photos.

The residual clay deposits in the Meridian Aggregates Quarry vary in grade both vertically and horizontally. The residual clays vary from kaolinite-rich to chlorite-illite-rich horizontally. This variation in clay grade appears to be controlled by the distribution of the bedrock composition. The kaolinite-rich residual clays are located above the St. Cloud Granite and the porphyritic rhyolite dike. The amount of chlorite and illite increases in the dark metamorphic rocks and the gray reformatory granite, and is dominate in the residual material above the mafic dikes. The depth of weathering also varies horizontally, and is controlled by the northwest trending fault zone. The residual clays are deepest in the center of the fault zone, and thin to the north and south, away form the fault zone. The vertical variation is increase quartz feldspar, and biotite, $\pm$ hornblende with depth in residuum above the granitic and metamorphic rocks. The increase in these minerals is consistent with decreasing chemical weathering effects with depth.

Isoclinal Slump-folds in the Lower Pokegama Quartzite: Evidence for Seismicity and Slope Instability During Deposition of the Animikie Group

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The Early Proterozoic Pokegama Quartzite overlies Archean basement of the Superior Province in the northwestern part of the Animikie Basin, Minnesota. Its age is constrained by geologic relationships [1,2,3] and Pb isotope data on detrital and cross-cutting quartz [4] as between 2.17 and 1.95 Ga. The depositional environment of the very fine grained, lower Pokegama Quartzite has been interpreted as tidal flat, based on the nature of crossbedding in the sandy middle Pokegama Quartzite and suggested correlation and similarity to the better exposed Palms Formation in Wisconsin [5]. The soft sediment deformation we recognize in the lower Pokegama, mostly tight to isoclinal folds and refolded folds, may provide important information concerning tectonic activity in the Animikie Basin during this time interval.

Abundant evidence for slump-folds can be found in the only well-exposed outcrop in the lower Pokegama Quartzite (Figs. 1-6). It is located immediately north of Eveleth, MN. The outcrop is approximately 500 ft long and 5-8 ft high. It is characterized by interbedded siltstones and argillites with numerous thin, fine sandstone layers (up to several inches thick). Folding is generally very tight to isoclinal, and recumbent (Fig. 7), and these characteristics are suggested by Farrel and Eaton [6] to indicate:

- 1) long distant transport of the slumps and
 - 2) a southeasterly paleoslope, consistent with previous interpretations of shoreline position [5,7].
- Figures 1-6 are line drawings, from field photographs, of some of the fold noses. These folds correspond to type 3 refolded folds, defined by Ramsay [8,6,9]. In addition to the numerous isoclinal fold noses, shear surfaces and at least one sheath fold indicate substantial horizontal displacement [6,10].

The Pokegama Quartzite, as well as the Biwabik and Gunflint Iron-formations, are here interpreted to have been deposited in a tectonically active basin. This interpretation is based on:

- 1) evidence for soft-sediment deformation in the lower Pokegama Quartzite (this study);
- 2) evidence for soft-sediment deformation, observed in the Biwabik Iron-formation;
- 3) presence of early brecciation [11] and isoclinal folds in the Gunflint Iron-formation in Ontario;
- 4) great variation in facies of the Pokegama just below the contact with the Biwabik, in the eastern Mesabi district (Ron Graver, per. comm., 1990); and
- 5) sudden change in thickness of the Pokegama Quartzite and Biwabik Iron-formation across a presumed fault in the eastern Mesabi district [12].

Strike-slip faulting in the region north of the Animikie Basin at about 1.95 Ga has been documented by Peterman and Day [13] using Rb-Sr dating of pseudotachylite in the Rainy Lake-Sein River fault system. They interpret the faulting to be a result of stresses associated with one of the Early Proterozoic, circum-Superior orogens, including the Penokean, as described by Hoffman [14]. The shales and turbidites of the Virginia and Thompson Formations, which form the upper part of the Animikie Group, are interpreted to have been deposited in a foreland basin associated with the Penokean Orogen [1]. Understanding the tectonic setting of the Animikie Basin prior to turbidite deposition clearly has important implications for understanding the Early Proterozoic history in the Great Lakes Region. The location of the Animikie Basin across the Great Lakes tectonic zone [15], and the location of Penokean magmatism generally between the Superior Province and the

Minnesota River Valley Province makes the sedimentary rocks within the Animikie basin important for evaluating the nature and location of the pre-Penokean continental margin. An oblique extensional setting, either driven by or associated with, strike slip faulting is suggested as a working model for early Animikie Group deposition. Such a setting could be associated with the passive margin side of a back arc basin (such as seen between Japan and China, and consistent with the interpretation of Van Schmus [16] and Southwick *et al.* [1]). The time interval for tectonic activity during deposition of the Pokegama Quartzite may be constrained between 2.17 and 1.95 Ga. The 1.95 Ga Pb-Pb age is from quartz gash veins in the upper Pokegama Quartzite. Additional age constraints for pseudotachylites and quartz veins in the basement and sedimentary rocks of the region, in conjunction with an understanding of their kinematic significance, may lead to important further constraints on the early evolution of the Animikie Basin.

References: [1] Southwick, D.L. *et al.*, 1988, MN Geol. Sur., Report of Investigations 37; [2] Southwick, D.L., and Day, W.C., 1983, Can. Jour. Earth Sci., v.20, p.622; [3] Hanson, G.N., and Malhotra, R., 1971, Geol. Soc. America Bull., v.82, p.1107; [4] Hemming *et al.*, 1990, EOS, v.71, p.654; [5] Ojakangas, R.W., 1983, Geol. Soc. America Mem. 160, p.49; [6] Farrel, S.G., and Eaton, S., 1987, Geol. Soc. Spec. Pub. no 29; [7] Morey, G.B., 1972, MN Geol. Sur. Centennial Vol; [8] Ramsay, J.G., 1967, Folding and Fracturing of Rocks, McGraw-Hill, New York; [9] Ramsay, J.G., and Huber, M.I., 1987, The Techniques of Modern Structural Geology, v.2. Folds and Fractures, Academic Press; [10] Allen, J.R.L., 1982, Sedimentary Structures, Their Character and Physical Basis, Dev. in Sed. 30B, Elsevier; [11] Franklin, J.M. *et al.*, 1972, IGC Field Excursion C34; [12] Gundersen, J.N., and Schwartz, G.M., 1952, MN Geol. Sur. Bull. 43; [13] Peterman, Z.E. and Day, W., 1989, Geology, v.17, p.1089; [14] Hoffman, P.F., 1988, Ann. Rev. Earth and Plan. Sci., v.16, p. 543; [15] Sims, P.K. *et al.*, 1980, Geol. Soc. America Bull., v.91, p.690; [16] Van Schmus, 1976, Phil. Trans. R. Soc. Lond., v.280, p.605.

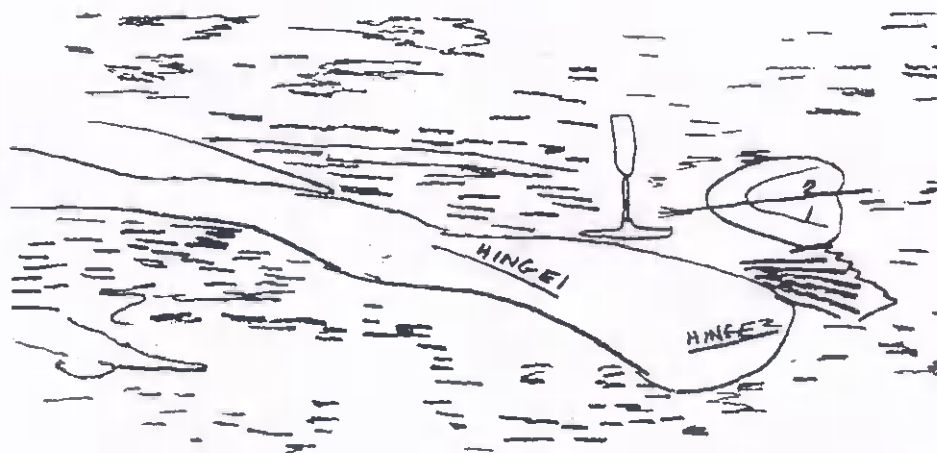


Fig. 1 Relatively large area of converging fold features. Heart-shaped sand body and elongate refolded fold are interpreted as type 3 refolded folds of Ramsay [8]. Note the fanning cleavage in the argillite, between the refolded folds. Hammer for scale.

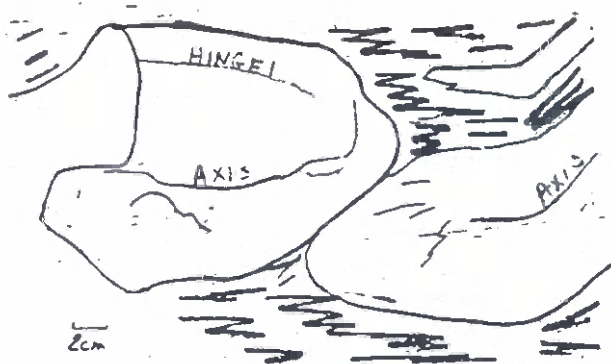


Fig. 2 A pair of fold noses. Hinge one (labeled) clearly visible on the nose to the left. It is not possible to tell if the nose on the right is refolded. Note scale bar at lower left of drawing.



Fig. 3 Fold nose with several sandy layers that are thickened in the hinge and thinned to boudinaged on the limbs. The box drawn on this figure is the approximate location of Fig. 4. Note scale bar at lower left of drawing.



Fig. 4 Detail of Fig. 3. Note thinning to separation of the limbs and thickening in the hinge of the sandier layer.



Fig. 5 An early tight fold refolded by a later tight recumbant fold. Note scale bar at lower of drawing.



Fig. 6 Recumbent isoclinal fold. Lower limb is thinned and bedding is quite disrupted. Note scale bar at lower left of drawing.

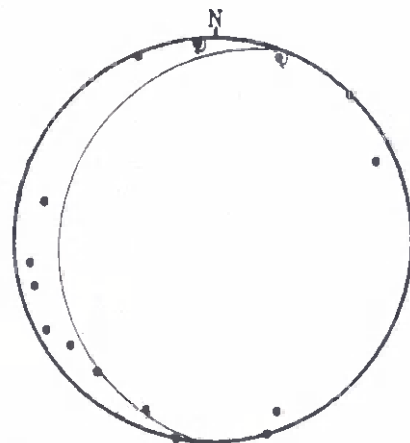


Fig. 7 Stereoplot of fold hinges in the Lower Pokegama. The plane representing the approximate attitude of bedding at the outcrop is also plotted [1].

Magmatic Evolution in the Midcontinent Rift: Evidence from Hypabyssal Rocks of the North Shore of Lake Superior

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The hypabyssal dikes and sills of northeastern Minnesota associated with the 1.1 Ga Midcontinent Rift are a suite of rocks distinct from the flows of the North Shore Volcanic Group, and although the dikes are far less significant volumetrically, they provide valuable information about processes operating during rifting.

In general, the diabase is ophitic, with pyroxenes 1-3 cm across containing varying amounts of enclosed plagioclase and olivine chadacrysts. Exsolution features in pyroxene are common, but do not dominate the grain population. In a few samples, coarse symplectites are present, with blebby oxides within the pyroxene. Some of these symplectites display exsolution lamellae in the pyroxene. This is evidence that the oxides and pyroxene formed comagmatically, and not simply as an alteration of a pre-existing phase such as olivine since exsolution features are unlikely to form in alteration products.

Plagioclase is present mainly as laths and fragments formed during rapid cooling, although a small number of phenocrysts are usually seen. These are not large (usually <2 mm), and many display prominent pits and dusty regions, interpreted as resorption features resulting from rapid decompression. Such an origin has been suggested for similar features in plagioclase from the Rio Grande rift (Lipman, 1969), and the southern Rocky Mountains (Doe et al., 1969). Plagioclase compositions range from laths and chill fragments of An_{50-65} , to phenocryst cores up to An_{80} . The phenocrysts often have rims of the "chill" composition, and a few are complexly zoned.

Olivine occurs as fine disseminated grains, glomerocrysts up to 3 mm, and occasional oikocrysts up to 1 cm. It is generally unzoned, with compositions mainly between Fo_{50} and Fo_{70} . Oxides make up a few percent of all samples, most being <1 mm across. Both ilmenite and spinel phases are present, and most grains display some oxyexsolution features.

Mineral thermometry (Table 1) performed on plagioclase and pyroxene gave crystallization temperatures of 1000 - 1150°C. Oxides yielded temperatures between 850°C and 1000°C, and oxygen fugacities approximately one log unit below the QFM buffer, which are consistent with results from the Portage Lake Volcanics (Paces, 1988). Oxide phases re-equilibrate rapidly with a cooling liquid, and thus the temperatures obtained for the oxides are probably best interpreted as near-solidus temperatures. The oxygen fugacities indicated are consistent also with the modelling by Miller et al. (1990) for the evolution of the Sonju Lake intrusion, which produced the best results when using oxygen fugacities one log unit below QFM.

The chilled margins were analyzed by INAA and microprobe fused bead techniques for bulk chemistry. Modelling of fractionation was done using the CHAOS program (a more

Table 1. Mineral geothermometer results.

Sample	Plagioclase		Pyroxene		Oxide	
	dry	$P_{H_2O}=0.5\text{kb}$			Temp.	$\log f_{O_2}$
SB-1 core	1211	1089	1100 $\pm$ 50		990	-12.3
	gdms	1192				
RR-1 core	1194	1064	1050 $\pm$ 50		853	-14.8
	gdms	1156				
BR-1	1192	1066	1000 (1150 @ 5kb)			
HP-1 core	1245	1138	1150 $\pm$ 50		961	-13.0
	gdms	1236				
CL-1						
B-5					860	-15.0

Temperatures in $^{\circ}\text{C}$. "gdms" = groundmass plagioclase.

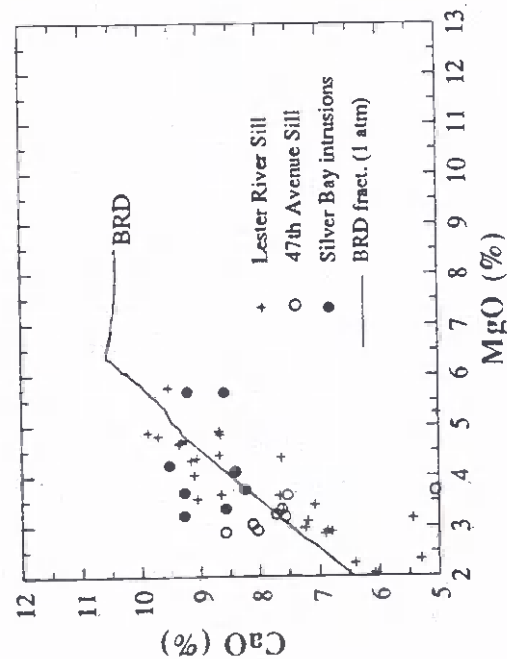


Fig. 2. Diagram showing hypabyssal material matching 1-atm model. (Silver Bay intrusions from Shank, 1990; J. Miller, pers. comm.; 47th Avenue Sill from K. Seifert, pers. comm.)

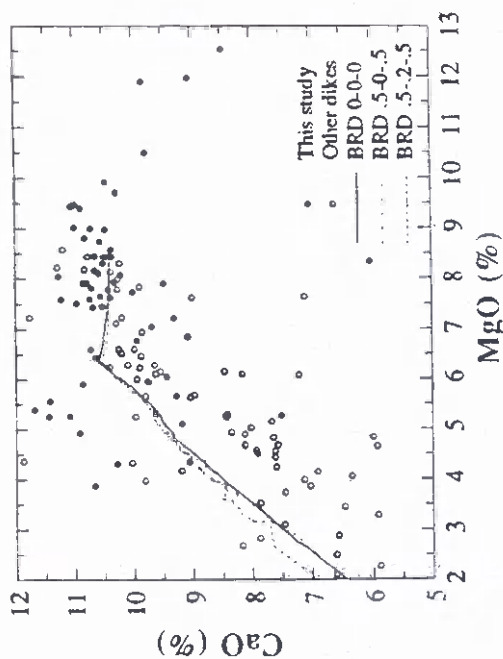


Fig. 1. Diagram showing 1-atm models and hypabyssal rocks. ("Other dikes" from Green et al., 1987)

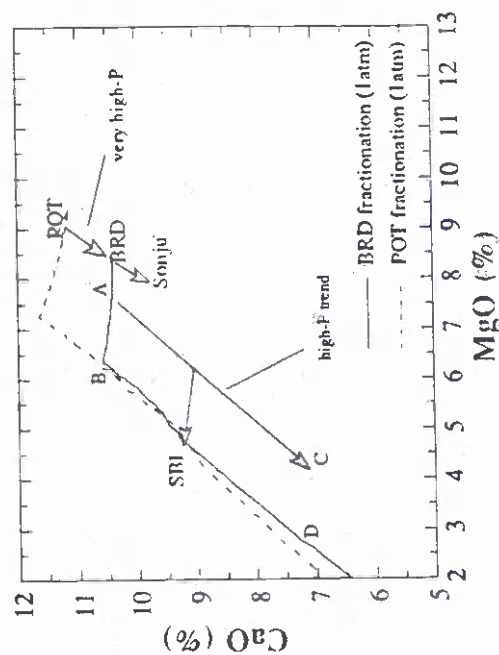


Fig. 3. Diagram showing possible fractionation paths for all hypabyssal rocks.

recent version of TRACE.FOR described by Nielsen, 1988a,b). One atmosphere modelling (Fig. 1) shows that the majority of the hypabyssal rocks formed at moderate pressures where the onset of pyroxene crystallization is earlier due to greater pyroxene stability at depth. This earlier crystallization results in the earlier depletion of Ca, leading to the offset of the data from the model trend. A number of hypabyssal rocks show evidence of fractionation at near surface levels (Fig. 2), falling on the model trend.

It is possible through polybaric fractionation to relate all of the varied hypabyssal rocks to a single primary parent, the high-Al "primitive olivine tholeiites," which are a common composition among the volcanic rocks associated with the Midcontinent Rift. In such a scenario, a primitive olivine tholeiite magma crystallizes ol+plag+pyx at depth (~10 kb?), driving the composition to lower Ca and Mg (BRD in Fig. 3). Continued fractionation at depth could lead to compositions similar to the Sonju Lake parent proposed by Miller et al. (1990). If a the magma of BRD composition is injected to an intermediate depth (~3-5 kb?), the crystallizing assemblage would lose pyroxene due to shrinkage of the pyroxene stability field, and the ol+plag crystallization would carry the liquids to lower Mg (point B in Fig. 3), where pyroxene would again crystallize, and the liquid compositions then migrate down in Ca, along the trend seen by many of the hypabyssal rocks (toward C in Fig. 3). If some liquids of BRD composition were actually injected to near surface regions, pyroxene crystallization could be delayed even further, and the liquids would follow the trend shown in the modelling for 1-atm pressure (toward D in Fig. 3). Sills such as the Lester River and 47th Avenue are in this group, as are the Silver Bay intrusions. In reality, there can of course be many cross trends, but the overall picture of multi-level fractionation is apparent.

The resorption features seen in the plagioclase; evidence for evolution at various levels in the crust, are consistent with the chemistry, which suggests the same process. The chemical similarity among samples of the entire suite is also evidence for lateral communication among chambers for great distances along the rift. These two processes have been inferred for the Mid-Atlantic rift in Iceland, which indicates that some modern rift processes were occurring at 1.1 Ga.

References:

- Doe, B.R., Lipman, P.W., Hedge, C.E., and Kurasawa, H. (1969). *Contributions to Mineralogy and Petrology*, 21, 142-156.
- Green, J.C., Bornhorst, T.J., Chandler, V.W., Mudrey, M.G.J., Meyers, P.E., Pesonen, L.J. and Wilband, J.T. (1987) *In: Mafic dyke swarms* (Halls, R.B. and Fahrig, W.F., ed.), Geological Association of Canada Special Paper 34, 289-302.
- Lipman, P.W. (1969). *Geological Society of America Bulletin*, 80, 1343-1354.
- Miller, J.D., Jr., Schaap, B.D. and Chandler, V.W. (1990). 36th Annual Institute on Lake Superior Geology, 66-68.
- Nielsen, R.L. (1988a) *Geochimica et Cosmochimica Acta*, 52, 27-38.
- Nielsen, R.L. (1988b) *Computers and Geosciences*, 14, 15-35.
- Paces, J.B. (1988) Ph.D. dissertation, Michigan Technological University, Houghton, 413p.
- Shank, S.G. (1990) M.S. thesis, University of Minnesota, Minneapolis, 130p.

SURFACE EXPRESSION OF MAJOR BEDROCK STRUCTURAL FEATURES

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Continental lithosphere in Minnesota is subdivided into a series of structural blocks bounded by fault zones that are components of Precambrian plate margins. Major fault zones in the crystalline basement have expression in landforms and surface sediments. For example, in western Minnesota, the Great Lakes Tectonic Zone is located at the southern limit of the Lake Agassiz plain; and in southwestern Minnesota, faults bounding the Fulda and Pipestone structural basins (Southwick and Mossler, 1984) correspond with the end moraine complex on the southwestern margin of the Des Moines lobe. Equivalence of basement structure and surface features will be described in three other areas: 1) Agassiz beach area in northwestern Minnesota, 2) Swanville spillway area in central Minnesota, and 3) north of Lake Mille Lacs.

In northwestern Minnesota, the beach complex at the margins of the Lake Agassiz plain forms a broad arc opening to the south and east. Northwest-trending faults in the Archean basement generally converge toward the curve of the arc and parallel the sides of the arc of beach ridges. Near Greenbush, MN, sharp variations in the elevation of the beach-ridge crest, mark the position of large areomagnetic gradients associated with the Vermillion Fault Zone. In central Minnesota, the St. Croix end moraine complex has a broad arc to the west between the Serpent Lake and Malmo structural discontinuities mapped by Southwick, Morey, and McSwiggen (1988). On the inside of the arc of the end moraine, several eskers trend perpendicular to and terminate at the position of the Malmo discontinuity. North of Lake Mille Lacs patterns of lowland peat and upland till are similar to the geometry of Proterozoic thrust duplexes. Eskers in this vicinity are generally located along areas of steep areomagnetic gradient and trend parallel to the contours.

Correspondence of major structural features in the Precambrian basement with geomorphic features and surface sediments helps to explain why linear features mapped on Landsat images appear to mark basement structures. Beach ridges, morainic margins, and some eskers are all visible as Landsat linear features; eskers trending perpendicular to structural features are not easily mapped as obvious linear features. Paleotectonic and recent earth movements along the lithosphere block boundaries influenced patterns of erosion and deposition. As a consequence, patterns of erosion and deposition visible as linear features on Landsat images show fidelity with structures in the Precambrian basement.

REFERENCES CITED

- Southwick, D.L., and Mossler, J.H., 1984, The Sioux Quartzite and subjacent regolith in the Cottonwood County Basin, Minnesota, in Southwick, D.L., ed., Shorter contributions to the geology of the Sioux Quartzite (Early Proterozoic), Southwestern Minnesota: Minnesota Geological Survey Report of Investigations 32, p. 17-44.
- Southwick, D.L., Morey, G.B., and McSwiggen, P.L., 1988, Geologic map of the Penokean Orogen, central and eastern Minnesota, and accompanying text: Minnesota Geological Survey Report of Investigations 37, 25 p.

THE LYNNE MASSIVE SULFIDE DEPOSIT, ONEIDA COUNTY, WISCONSIN

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The Lynne deposit is a volcanic- to volcanoclastic-hosted, Zn-Pb-Cu-Ag orebody located in the early Proterozoic magmatic terrane of northern Wisconsin. A preliminary ore reserve, based on the first 39 holes in an open-pit mine design, is calculated at 6.1 million tons grading 7.14% Zn, 0.34% Cu, 1.89% Pb, 3.09 opt Ag, and 0.013 opt Au. The mineralization is hosted by a gently-dipping sequence of fragmental rhyolites, chiefly lapilli to crystal tuffs, and less abundant dacite to andesite flows, volcanoclastic sandstones and siltstones. Facies relationships in the rhyolitic pyroclastic rocks to the north (down-dip) suggests proximity to a volcanic constructional feature. A footwall tonalite intrudes and partly encloses the lowermost part of the deposit, and a number of subvertical, east- to southeast-trending faults disrupt the down-dip extension of mineralization. Many of these faults are occupied by feldspar-phyric, rhyolitic to basaltic dikes.

The bulk of the Zn-Pb-Cu-Ag mineralization occurs within a sequence of chemical sedimentary rocks which thicken and coalesce in the central part of the deposit. Lenses, lobes and stratiform bodies of massive to semi-massive sulfide are interbedded with conformable talc units, chert, laminated to disrupted carbonate rocks, and narrow beds of volcanoclastic and sedimentary rocks. The talcose rocks underlie and partly enclose lenses of laminated, pyrrhotite-rich chert and sphalerite-rich massive sulfide, and also host disseminated sphalerite, pyrrhotite, and galena. The talcose unit is overlain by thick beds of massive sulfide and lenticular masses of carbonate and chert containing disseminated to bedded sulfides. The aggregate thickness of the sulfide-rich sedimentary rocks exceeds 325 feet in the center of the deposit; its lenticular nature and symmetry suggests that it may have formed as a hydrothermal mound, with an undetermined amount of replacement mineralization.

Sphalerite is the most abundant sulfide mineral, followed in abundance by pyrrhotite, galena, pyrite, and chalcopyrite. Tetrahedrite (var. freibergite) or polybasite, native silver, pyrargyrite, electrum, and native gold are also economically important minerals. The sulfide distribution and metal zonation is similar to the zoning documented in other volcanogenic massive sulfide deposits. Chalcopyrite and pyrrhotite are most abundant in the lowermost talcose unit, whereas silver minerals and galena are concentrated in diopside-rich cherts and cherty beds in the upper part of the deposit. Calc-silicate minerals, including diopside, ferrosalite, garnet, tremolite, and epidote, are widespread; most of these minerals formed as a result of decarbonation reactions during the emplacement of the footwall tonalite, or perhaps during the late stages of hydrothermal activity.

THICK-SKINNED BACKTHRUSTING IN THE FELCH-CALUMET TROUGHS REGION, NORTHERN MICHIGAN-- A COMPARISON WITH THE SOUTHERN ALPS

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The Felch and Calumet troughs region is on the south edge of the Superior craton. Rocks of the Wisconsin magmatic terranes were accreted to the craton approximately 1850 Ma along the north-verging Niagara fault, causing complex deformation and metamorphism of Archean basement and Early Proterozoic strata on the foreland. In the study area, deformation is characterized by thick-skinned, south-verging backthrusting and backfolding opposite the overall sense of north-verging deformation on the continental foreland. That near-recumbent minor folds with accompanying axial-planar subhorizontal foliation are evident in both Archean and Early Proterozoic rocks suggests the presence of crystalline-cored nappes, such as that of the Carney Lake block.

Deep tectonic levels are exposed in the Felch and Calumet troughs region, indicating major involvement of Archean rocks in the deformation. Both involvement of basement and the existence of backthrusts are common in younger orogens, such as in the southern Alps. Comparing a section of the 1850 Ma Penokean orogen in northern Michigan with a section in the 30 Ma southern Alpine orogen reveals several common features. Proceeding inward from the continental margin, both orogens have 1) accreted oceanic crust as shown by the presence of ophiolite; 2) a zone of thick-skinned, complex deformation with associated backthrusting and backfolding; 3) a master thrust along which strata were tectonically transported over a basement arch; and 4) inboard of the basement arch, deformation that is mainly thin skinned, but also involves some thrusting of basement rocks. The Alpine orogen consists of multiply deformed nappes, whereas deep erosion of the Penokean orogen makes recognition of nappes difficult. Nevertheless, the minor recumbent folds and a subhorizontal foliation in the Felch and Calumet troughs area are structures similar to those in the Alps, and their presence strongly suggests that nappes, now mostly eroded, may also exist in the Penokean orogen of northern Michigan.

EARLY PROTEROZOIC ROCKS IN THE MONICO, WISCONSIN AREA:
IMPLICATIONS ON THE WISCONSIN MAGMATIC TERRANE

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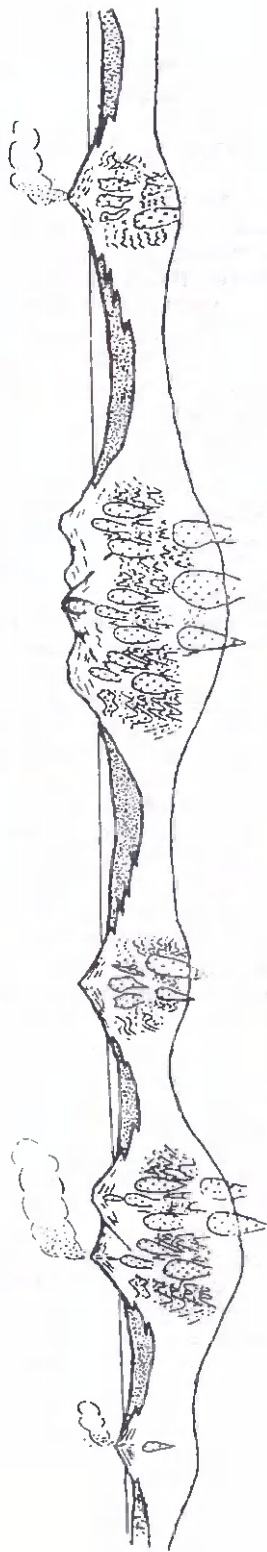
The Wisconsin magmatic terrane is a major east-trending belt of Early Proterozoic volcanic and plutonic rocks in the Lake Superior region. The Monico area is a "window" into the Early Proterozoic rocks through the Pleistocene deposits that blanket most of northern Wisconsin, and, therefore, may afford an opportunity to determine the relationships between major units within the volcanic belt. This paper presents preliminary data from a project funded by a Faculty Development Grant from UW-Oshkosh, with support from the Wisconsin Geological Survey, and the U.S. Geological Survey.

Similar to other parts of the Wisconsin magmatic terrane, at least two distinctly different sequences of rocks are present in the Monico area. One sequence, exposed mainly north of Highway 8, consists mainly of amphibolite-facies gneissic rocks with little preservation of primary features. The dominant lithology is a foliated granitoid gneiss with abundant mafic blocks. Numerous segmented mafic dikes are also present.

The other sequence, exposed mainly south of Highway 8, consists of several mafic to felsic successions of greenschist-facies volcanic rocks with subordinate volcanogenic sedimentary rocks. The repetitions in successions may be due to a combination of tight folding and faulting. Several large metadiabase dikes and the "Jennings granite" intrude the volcanic successions. Although pillow basalts, debris flows, and flow-banded rhyolite and felsic breccias are dominant in the Monico area, drill cores to the east and west of the area of outcrop contain higher proportions of sedimentary rocks. This suggests that rocks in the Monico area may represent a volcanic center (a volcanic island?) within the magmatic terrane. By contrast, the areas with abundant sedimentary rocks may represent intra-arc or back-arc basins between volcanic centers.

The two major sequences of rocks in the map area are presumably in fault contact, and it is probable that the gneissic rocks represent uplifted, deeper levels of volcanogenic rocks that were formed during earlier stages of subduction within a mature island arc. By contrast, the greenschist-facies rocks may represent later products of the general subduction event. The fault separating the two rock sequences may be the result of deformation during docking of the magmatic terrane with rocks of the Superior Craton to the north. Thus, the rocks exposed in the Wisconsin magmatic terrane may represent various tectonic slices of a mature island arc and associated intra-arc and back-arc basins.

Sketch of hypothetical east-west (longitudinal) section along the Wisconsin magmatic terrane showing various stages of development of volcanic centers along the island arc.



The Geology and Geophysics of major post-Keweenawan faults in the eastern Lake Superior region

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The eastern Lake Superior shoreline has a characteristic saw-tooth outline in which promontories are primarily occupied by Middle Keweenawan volcanics of the 1.1Ga Midcontinent Rift of North America (MCR), and embayments by Upper Keweenawan clastics. This pattern appears to be generated by major ENE to WSW faults, some of which are related to Archean structures within the southern Superior Province. At Mamainse Point, more than 5km of volcanics are bound against sandstones to the south by a fault that appears, in new Ontario Geological Survey aeromagnetic data, to extend inland along the southern margin of the adjacent greenstone belt. The Montreal River fault, possibly related to the Kapuskasing structure, defines the northern margin of these greenstones and extends into rift strata underlying eastern Lake Superior in GSC-GLIMPCE aeromagnetic data. At Havilland Bay, a 500m thick succession of Jacobsville sandstone has been upturned and folded against a little-recognised fault exposed directly alongside Highway 17. Further east-west faults have been observed bounding Keweenawan strata in the Goulais Bay area and at Grindstone Point.

Whilst the exact nature of these faults is unclear, significant vertical displacements across the Mamainse Point and Havilland Bay faults is suggested from detailed gravity profiles collected during 1990. Regional potential field data indicate the lateral extent of many of the faults and suggest broad structural units normal to the rift axis. This contrasts with post-Keweenawan faults in the western lake region which are generally parallel to the axis of the rift. The change in structural style from west to east is highlighted in the centre of the lake, where a series of arcuate fault segments appear to link the Isle Royale and Michipicoten Island faults via Superior Shoal (Teskey et al., 1991). Sampling with a submersible has revealed a complex structure for Keweenawan volcanics exposed at the Shoal, possibly involving drag folding and block rotations (Manson and Halls, 1991).

Constraints on the sense and timing of the eastern faults will have relevance to models describing the closure of the MCR, possibly requiring a Grenville influence, and offer a method for quantifying post-Keweenawan deformation within the southern Superior Province.

Manson, M.L., and Halls, H.C., 1991, An investigation of Superior Shoal, central Lake Superior, with a manned submersible, *in press*, C.J.E.S.

Teskey, D.J., Thomas, M.D., Gibb, R.A., Dods, S.D., Kucks, R.P., Chandler, V.W., Fadaie, K., Phillips, J.D., 1991, High resolution aeromagnetic survey of Lake Superior, EOS, V.72, No.8

GEOPHYSICAL INVESTIGATIONS OF THE MIDCONTINENT RIFT IN EASTERN LAKE SUPERIOR USING VARIABLE MAGNETIZATION MODELING

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Magnetic anomalies over eastern Lake Superior are very useful in tracing the subsurface extent and geometry of the Keweenaw volcanic rocks of the Midcontinent Rift. In 1987, a high resolution aeromagnetic survey was flown over Lake Superior as part of the Great Lakes Multidisciplinary Program on Crustal Evolution. In order to take full advantage of these new data, improved quantitative magnetic modeling techniques have been developed and applied to the volcanic rocks. The Keweenaw basalts have retained a strong remanent magnetization derived when they cooled through the Curie point isotherm of magnetite. Post-depositional structural deformation of these rocks has rotated the remanent magnetization vector resulting in a spatially varying direction and intensity of magnetization when vectorially added to the induced magnetization vector. An algorithm to accommodate these variations in magnetization has been formulated and tested and has been applied to the volcanic rocks of eastern Lake Superior.

The magnetic modeling procedure, which is based on the equivalent point source concept, is termed the equivalent point dipole (EPD) method, and calculates the magnetic response of a given volume of anomalous magnetization by summing the magnetic fields due to a series of point dipoles of specified spacing contained within the volume. This approach allows the direction and magnitude of magnetization to vary freely over an anomalous unit. The accuracy and speed of this calculation are directly dependent on the point dipole spacing. The optimum spacing minimizes calculation time, but still results in acceptable calculation error. Given the simplicity of the dipole calculation and the speed of modern computing facilities, this is fortunately not a problem. In general, a dipole spacing equal to one tenth the distance between the observation plane and the point dipoles yields errors less than one percent. Figure 1 shows comparisons of the EPD calculation with the conventional method of anomaly calculation (Talwani and Heirtzler, 1964).

The EPD method has been applied on a two dimensional basis to profiles that have been studied with the gravity and seismic reflection methods in eastern Lake Superior. These profiles include recently released seismic reflection sections with up to 8 s of TWTT as well as previously available GLIMPCE data with up to 16 s of TWTT. On these sections, the Keweenaw basalts are clearly imaged as a series of strong, laterally continuous reflections with dips generally ranging from -30 to +30 degrees. Extensive paleomagnetic studies in the Lake Superior region indicate that the basalts possess both a normal and reversed remanent magnetization component in addition to the induced component. Assuming original horizontality of the basalt flows, the apparent dips derived from the seismic reflection sections are used to rotate the remanent magnetization vector back to the horizontal in the plane of the profile. The rotated remanent vector is then added to an induced magnetization vector, resulting in a spatially varying direction and magnitude of total magnetization.

Modeling results indicate that the consideration of variable magnetization will provide much greater confidence in the structural interpretations of the Keweenaw basalts. Preliminary models in eastern Lake Superior suggest that a large volume of reversely polarized rocks is necessary to account for the observed aeromagnetic anomalies.

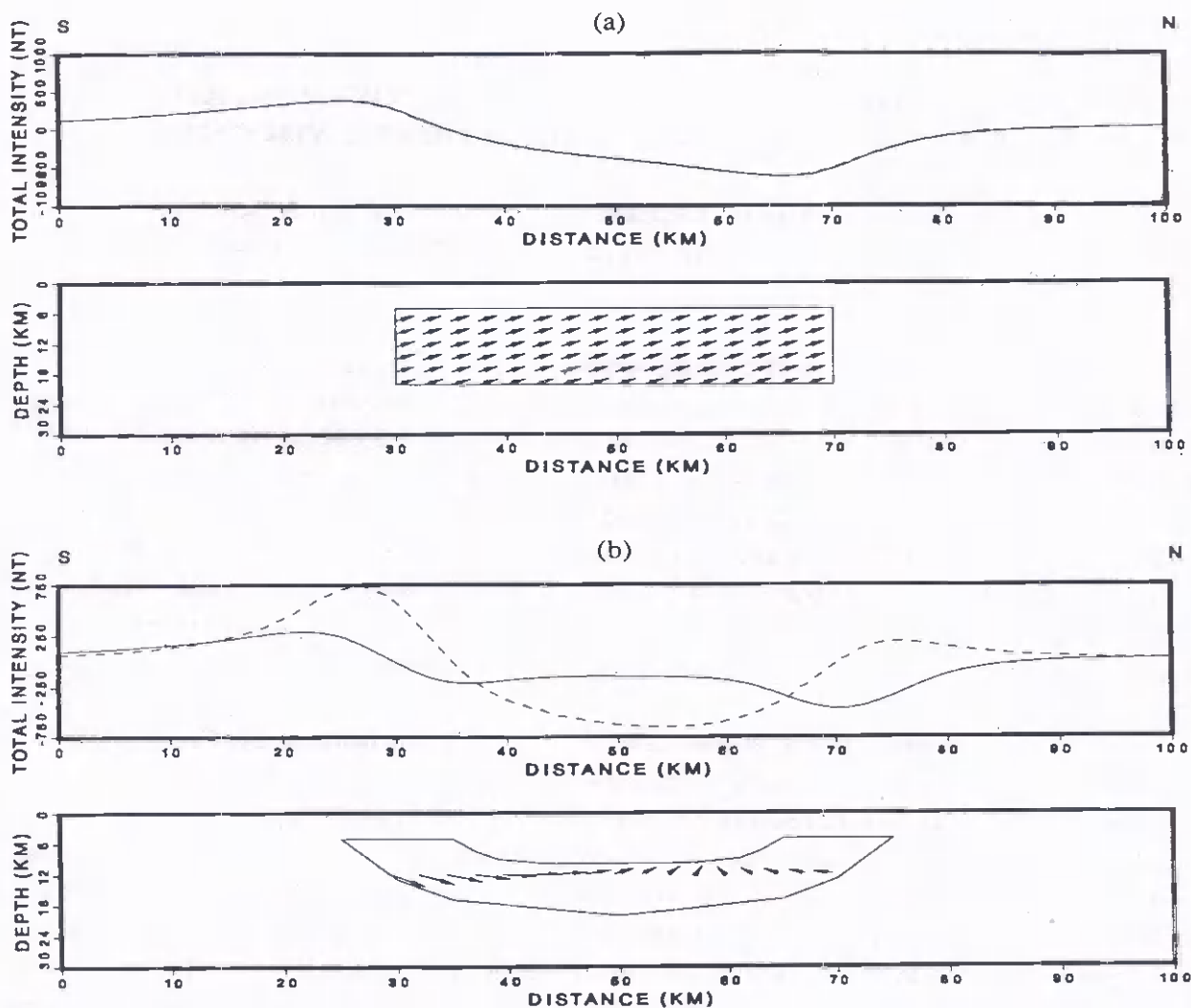


Figure 1. (a) The magnetic anomaly due to combined induced and remanent magnetization calculated by the EPD method (dashed) and the Talwani and Heirtzler method (solid). Note that these are essentially coincident over the entire length of the profile. The total magnetization vector in the plane of the profile is shown for every fifth dipole. (b) The magnetic anomaly due to combined induced and remanent magnetization with a gradational rotation of the remanent vector using the EPD method (dashed) and with homogeneous magnetization using the Talwani and Heirtzler method (solid). A single horizontal plane of total magnetization vectors is shown. The induced and remanent magnetization vectors and the disturbance of the remanent vector are compatible with conditions in the Lake Superior region and the volcanic rocks of the Midcontinent Rift.

Reference

Talwani, M. and Heirtzler, J., 1964, Computation of magnetic anomalies caused by two-dimensional structures of arbitrary shape. IN: Computers in the Mineral Industries, 1. Stanford Univ. Publ. Geol. Sci., 9(1): 464-480

A PRELIMINARY STUDY OF REJUVENATED MOVEMENT ALONG A PRECAMBRIAN FAULT, ST. CROIX COUNTY, WISCONSIN

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The eastern margin of the Midcontinent Rift system is marked by the Hastings-Lake Owen fault in western Wisconsin. Precambrian displacement along this high angle fault has been estimated at approximately 3,000 m. (Craddock, 1972) based upon geophysical evidence. A number of workers have suggested that the Hastings-Lake Owen fault was reactivated in the late Cambrian, causing thinning of the Cambrian section and an unconformity between the Cambrian and Ordovician sequences in Minnesota (Morey and Rensink, 1969; Cavaleri, et. al., 1987). Evidence from a number of exposures in St. Croix County, Wisconsin supports these views, and further refines the timing and amount of post-Precambrian movement along the fault.

The surface expression of the Hastings-Lake Owen fault in St. Croix County is a series of low escarpments with a northeast trend formed by differential erosion of the softer Cambrian sandstones to the west which have been displaced upward against more resistant Ordovician dolomites to the east. A quarry along this trend cut into dolomites of the Lower Ordovician Prairie du Chien Group shows evidence of this displacement. In sharp contrast to the relatively flat-lying bedrock units in this region, the strata in the quarry dip approximately 20° to the east. These strata dip away from the fault on its downthrown side, and these dips were most probably caused by drag. The displacement of the Cambrian sandstones against Lower Ordovician dolomites and the drag folding within the dolomites both demonstrate post-Early Ordovician movement along the fault. In addition, features within the dolomite itself provide evidence for movement of the fault in the Early Ordovician during deposition of the sediments. The beds in the quarry thicken away from the fault, with lower strata showing higher dips than those above. Sharply truncated stromatolite beds, thick dolomitic conglomerates, erosional relief along contacts, and mudcracks all attest to periodic erosion and exposure of the sea floor during deposition of the Prairie du Chien Group at this site, perhaps due to recurrent small movements along the fault.

The amount of Post-Precambrian displacement along the Hastings-Lake Owen fault in this region can be determined at exposures in the vicinity of Hudson, Wisconsin. Cambrian sandstones have been displaced upward approximately 85-100 m. against Ordovician strata along the fault. Along the Cottage Grove fault which parallels the Hastings-Lake Owen fault to the northwest, displacement is even greater, approximately 115-125 m. The evidence gathered in St. Croix County demonstrates later recurrent movements and greater Post-Precambrian displacement than has previously been reported for the Precambrian faults in this region.

References Cited

- Cavaleri, M., Mossler, J.H. and Webers, G.F., 1987, The Geology of the St. Croix River Valley, in Balaban, N.H., Ed., *Field Trip Guidebook for the Upper Mississippi Valley, Minnesota, Iowa and Wisconsin*. Minnesota Geological Survey, Guidebook Series #15, p. 23-43.
- Craddock, C., 1972. Keweenawan Geology of East-central and Southeastern Minnesota, in Sims, P.K. and Morey, G.B., Eds, *Geology of Minnesota: A Centennial Volume*. Minnesota Geological Survey, p. 416-424.
- Morey, G.B. and Rensink, D.G., 1969. Rejuvenated Precambrian faults as a cause of Paleozoic structures in southeastern Minnesota. *Annals of the Institute of Lake Superior Geology*. 15th, Wisconsin State University, Dept. Geol., Oshkosh, WI, May 8-9.

GEOCHRONOLOGY OF THE DULUTH COMPLEX: A PROGRESS REPORT

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Recent high-precision dating of volcanic rocks associated with the Midcontinent Rift have contributed much toward understanding the timing, duration, and tectonomagmatic evolution of the 1.1-Ga rifting event. However, similar geochronological control for associated plutonic rocks is not yet available. The primary objective of the present study is to date individual gabbroic intrusions within the Duluth Complex in northeastern Minnesota using high-precision U-Pb techniques (1) to determine the temporal range of intrusive activity within several well-studied areas of the complex, as well as between these intrusions and the overlying volcanic rocks, and (2) to test models, which have previously been based on geologic mapping and geophysical interpretation, for the emplacement of the Duluth Complex.

The Duluth Complex is large, composite mafic intrusive supersuite, which was emplaced at shallow depths (<7 km) beneath a comagmatic edifice of plateau basalt during the development of the Midcontinent Rift (Fig. 1). Multiple intrusions were also emplaced higher into the volcanic pile, with the most voluminous of these being the Beaver Bay Complex. The Duluth Complex is composed of several lithologically distinctive rock series, previously interpreted to be temporally distinct (Weiblen & Morey, 1980). The oldest intrusive rocks are a layered suite of gabbroic cumulates in the northern area, termed Nathan's layered series (Fig. 1). Their evolved compositions and reversed magnetic polarity suggest that these rocks may be similar in age to the nearby Logan sills (1109 ± 2 Ma; Davis & Sutcliffe, 1985). These gabbros are intruded by a structurally complicated suite of dominantly plagioclase cumulates, termed the anorthositic series (Fig. 1), which occur throughout the complex and are thought to have intruded as plagioclase crystal mushes (Miller & Weiblen, 1990). Anorthositic series rocks are intruded throughout the complex by layered intrusions of troctolitic to gabbroic cumulates, collectively termed the troctolitic series. The apparent truncation of aeromagnetic patterns related to SE-dipping layering in intrusions along the unexposed western margin of the Duluth Complex (Fig. 1) led Miller et al. (1990) to speculate that troctolitic series intrusions young to the south as a result of successive intrusive overplating. A felsic series also comprises a significant portion of the Duluth Complex (Fig. 1) but was not included in this geochronologic study.

Differentiated samples from seven mafic intrusive bodies were chosen that, based on geologic and geophysical evidence, span the temporal and spatial (areal and stratigraphic) limits of intrusive activity in the Duluth Complex (Table 1; Fig. 1). Between 30 and 40 kg of rock was processed for each sample yielding clear zircon ($\pm$ baddeleyite) grains lacking obvious cores or rims. Air-abrasion and hand-picking yielded crack- and inclusion-free grains, which were analyzed individually or as 2-5 grain aggregates weighing 30 to 150 μ g. U contents range from 200 to 1000 ppm, and most fractions are less than 1.5% discordant. Preliminary ages for five of these samples are reported in Table 1. The two anorthositic samples (FC1, AS3) plus one troctolitic series ferrogabbro (D1) yield identical ages at the 95% confidence level. Fractions from all three rocks regressed together result in an age of 1099.1 ± 0.6 Ma with a lower intercept age of -1 ± 40 Ma (MSWD = 1.3). The troctolitic series olivine gabbro (PG2), as well as the hypabyssal ferrodiorite from the Beaver Bay Complex (SBG2), yield younger ages of 1096.1 ± 0.8 and 1095.9 ± 0.5 Ma, respectively, which are clearly resolved from the older ferrogabbro and anorthosite dates. Although additional analyses are required before final age determinations are made, the following have been established:

- Although the onset of igneous activity as represented by Nathan's layered series has not yet been determined, the bulk of the Duluth Complex and associated hypabyssal intrusions were emplaced between 1099 and 1096 Ma. This further supports previous observations that volumetrically most Keweenawan igneous activity occurred over a time span between 1099 and 1094 Ma (Davis & Sutcliffe, 1985; Davis & Paces, 1990; Van Schmus et al., 1990). Since parts of the Duluth Complex are older than the normal-polarity lavas exposed along rift margins, these intrusive rocks may represent a means of sampling magmas associated with lavas that are more deeply buried within the central rift graben.
- The relative ages of intrusive rocks based on their magnetic polarity must be viewed with considerable caution. Although all of the analyzed rocks possess normal magnetic polarity, three of the intrusive bodies have emplacement ages of 1099 Ma, older than the major R-N magnetic reversal placed at about 1097.6 ± 3.7 Ma (Fig. 1; Davis & Sutcliffe, 1985). This disparity is likely related to the slow cooling of

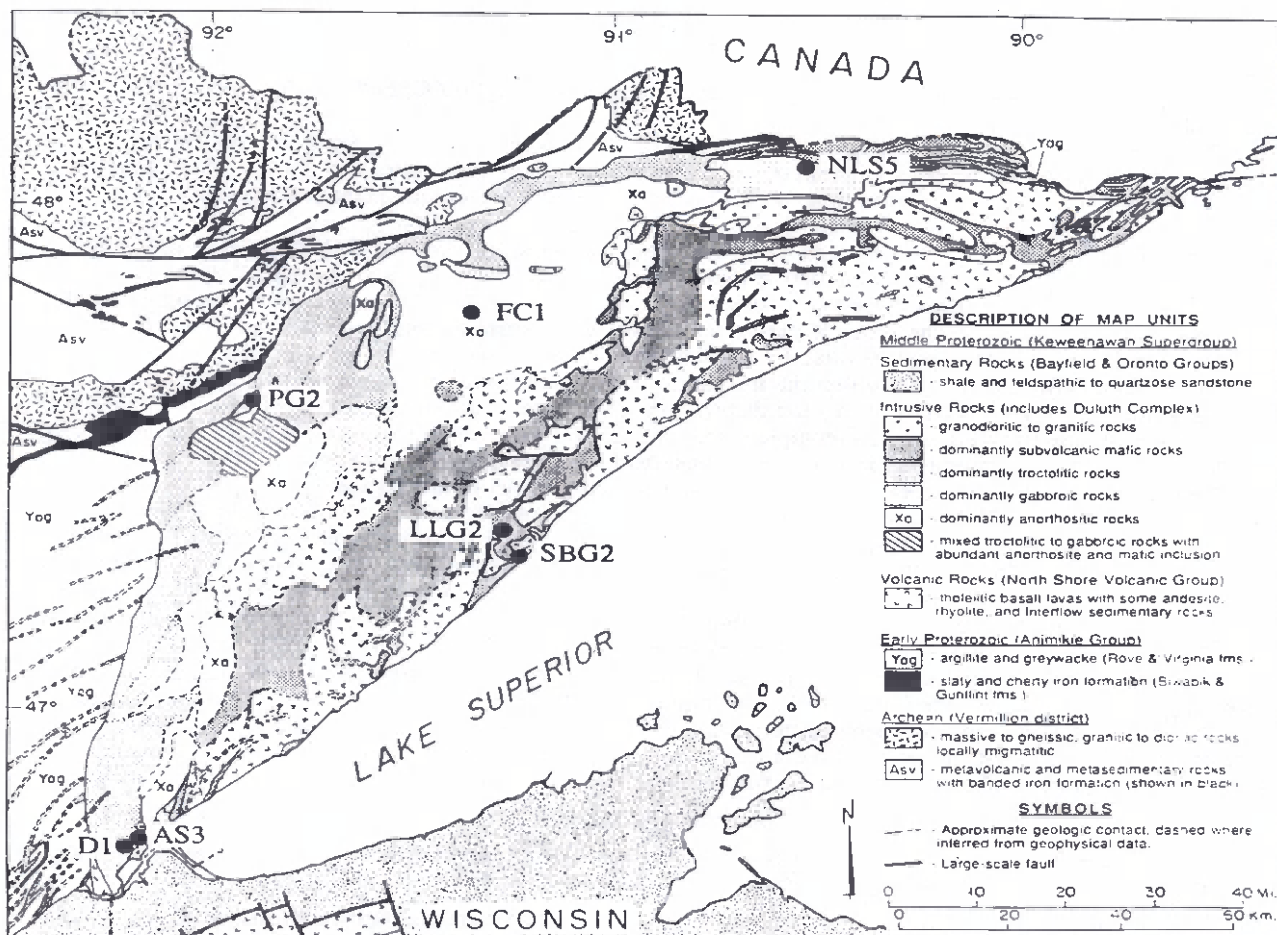


Figure 1. Generalized geology of northeastern Minnesota showing samples collected for U-Pb isotope analyses.

Table 1. Preliminary U-Pb ages for zircons from Duluth Complex and related intrusions

Sample	Rock Series	T-R-Sec.	Rock Type	Upper Intercept Age (Ma) $\pm 2\sigma$ error	No. of analyses	Lower Intercept Age (Ma) $\pm 2\sigma$ error
D1	Troctolitic	49-15-1	ferrogabbro	1099.0 $\pm$ 0.8	3	-2 $\pm$ 41
PG2	Troctolitic	59-12-8	olivine gabbro	1096.1 $\pm$ 0.8	3	0**
AS3	Anorthositic	49-14-6	gabbroic anorthosite	1098.9*	1	
FC1	Anorthositic	61-8-10	gabbroic anorthosite	1099.2 $\pm$ 1.7	4	0**
NLS5	Nathan's L.S.	64-2-2	olivine gabbro	in progress		
LLG2	Beaver Bay Complex	56-7-6	ferrogabbro	in progress		
SBG2	Beaver Bay Complex	56-7-29	ferrodiorite	1095.9 $\pm$ 0.5	4	5 $\pm$ 7

* $^{207}\text{Pb}/^{206}\text{Pb}$ age from single analysis

**Regression forced through 0 Ma lower intercept due to clustering of data near concordia

these plutonic rocks between zircon crystallization temperatures (~900°C) and the Curie point of the Fe-Ti oxides (<590°-350°C).

- The similar ages of anorthositic series rocks (AS3 & FC1) taken from widely separate areas of the complex suggest that the emplacement of these rocks occurred as a restricted temporal event throughout the Duluth Complex around 1099 Ma. This is consistent with their unique petrogenesis (Miller & Weiblen, 1990).
- The essentially identical 1099-Ma age of anorthositic and troctolitic rocks at Duluth (AS3 & D1), while not contradicting field relations indicating that the anorthositic rocks are older, does lead to the speculation that the petrogenesis of these two series may be more closely linked than previously thought. At the very least, it implies that the types of parent magmas that gave rise to these two rock series were either very closely related or were generated by mechanisms that were very nearly synchronous.
- Speculation (Miller et al., 1990) that the troctolitic series intrusions along the western margin young to the south is strongly contradicted by the distinctly younger age of the troctolitic series sample from the northwest (Kawishiwi) part of the complex (PG2; 1096 Ma) compared to the sample at Duluth (D1; 1099 Ma). Given the complexity of intrusive relationships in the Kawishiwi area (Severson & Hauck, 1990), it seems likely that troctolitic series rocks of various ages may exist in this region.
- The similarity of 1096-Ma ages between the Kawishiwi-area olivine gabbro (PG2) and the ferrogabbro (SBG2) representing the youngest intrusive unit of the hypabyssal Beaver Bay Complex (Miller, 1988) implies that magmas were simultaneously emplaced at several stratigraphic levels within the volcanic pile, at least late in the intrusive history. Dating of the Lax Lake gabbro, which mapping shows to be among the earliest intrusions in the Beaver Bay Complex (Miller, 1988), will determine whether intrusive activity in this hypabyssal environment began as early as it did in the deeper Duluth Complex.

In summary, high-precision dates generated by this study place very important constraints on the timing and emplacement mechanisms for the Duluth Complex and related intrusions, as well as providing additional data bearing on the broader evolution of the Midcontinent Rift. These preliminary results give cause to rethink previously proposed concepts hypothesized from field, geochemical, and geophysical data, and offer incentives for further integration of these data toward better understanding of rift processes.

REFERENCES CITED

- Davis, D. W., & Paces, J. B., 1990, Time resolution of geologic events on the Keweenaw Peninsula and implications for development of the Midcontinent Rift system: *Earth Plan. Sci. Letters*, v. 97, p. 54-64.
- Davis, D.W., & Sutcliffe, R.H., 1985, U-Pb ages from the Nipigon plate and northern Lake Superior: *Geol. Soc. Am. Bull.*, v. 96, p. 1572-1579.
- Miller, J.D., Jr., 1988, Geologic map of the Silver Bay and Split Rock Point NE quadrangles, Lake County, Minnesota: *Minn. Geol. Surv. Misc. Map M-65*, scale 1:24,000.
- Miller, J.D., Jr, Chandler, V.W., Southwick, D.L., & Cambray, F.W., 1990, Style of emplacement of the Duluth Complex: *Geol. Soc. Am. Abstr. with Programs*, v. 22, p. A369.
- Miller, J.D., Jr., & Weiblen, P.W., 1990, Anorthositic rocks of the Duluth Complex: examples of rocks formed from plagioclase crystal mush: *J. Petrol.*, v. 31, p. 295-339.
- Palmer, H.C., & Davis, D.W., 1987, Paleomagnetism and U-Pb geochronology of volcanic rocks from Michipicoten Island, Lake Superior, Canada: precise calibration of the Keweenaw polar wander track: *Precambrian Res.*, v. 37, p. 151-171.
- Severson, M.J., & Hauck, S.A., 1990, Geology, geochemistry, and stratigraphy of a portion of the Partridge River intrusion: Duluth, Univ. of Minn., Nat. Resources Research Inst. Tech. Report NRRI/GMIN-TR-89-11, 236 p.
- Van Schmus, W.R., Martin, M.W., Sprowl, D.R., Geissman, J., & Berendsen, P., 1990, Age, Nd and Pb isotopic composition, and magnetic polarity for subsurface samples of the 1100 Ma Midcontinent Rift: *Geol. Soc. Am. Abstr. with Programs*, v. 22, p. A174.
- Weiblen, P.W. and Morey, G.B., 1980, A summary of the stratigraphy, petrology, and structure of the Duluth Complex: *Am J. Sci.*, v. 280-A, p. 88-133.

MANGANESE MINERALIZATION IN EARLY PROTEROZOIC IRON-FORMATION OF THE EMILY DISTRICT, CUYUNA RANGE, EAST-CENTRAL MINNESOTA

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Early Proterozoic strata of the Emily district at the far northern end of the Cuyuna Iron Range define the southwestern closure of the Animikie basin in east-central Minnesota (Southwick and others, 1988). As such, the rocks of the Emily district are correlative with strata of the well known Animikie Group of the Mesabi range. However, unlike the monoclinical nature of the Mesabi range, strata in the Emily district are thrown into a series of broad, open, eastward-plunging folds with near-vertical axial planes. Geometric relationships imply that the basal contact of the Animikie Group overlies an unconformity cut onto older folded rocks of the North range (Chandler and Malek, 1991). That unconformity marks the boundary between twice-deformed rocks of the Penokean fold-and-thrust belt and the once-deformed rocks of the Animikie basin.

On the Mesabi range, the Animikie Group consists of a lower quartz arenitic sequence (Pokegama Quartzite), an intermediate iron-rich sequence (Biwabik Iron Formation), and an upper black-shale-graywacke sequence (Virginia Formation). In the Emily district, however, the stratigraphic position of the Biwabik is occupied by several lenticular units of iron-formation intercalated within both Pokegama- and Virginia-like materials.

The main iron-formation of the Emily district—termed Unit A of the Ruth Lake area—can be divided into seven lithotopes (Fig. 1). They are (1) an epiclastic lithotope of quartz-rich siltstone and shale; (2) a mixed epiclastic-jaspery-chert lithotope; (3) an oolitic and pisolitic lithotope; (4) a thick-bedded lithotope of cherty or granular iron-formation; (5) a mixed thick- and thin-bedded lithotope characterized by thick intervals of slaty or nongranular iron-formation; (6) a thin-bedded lithotope consisting of laminae to very thin beds of nongranular iron-formation; and (7) a ferruginous chert lithotope. In general, lithotopes 1, 2, and 3 contain primary hematite and have textural attributes indicative of the oxide (hematite) facies of iron-formation. In contrast, lithotope 6 contains appreciable carbonates or silicates and has textural attributes indicative of the carbonate facies of iron-formation. Lithotopes 4 and 5 are interlayered and contain mixtures of oxides (hematite-magnetite) and silicates, and thus were deposited in generally similar sedimentological regimes in waters variably affected by currents and at depths intermediate between oxides and carbonate facies. The sedimentological significance of lithotope 7 is uncertain. It is a thin-bedded laminated unit deposited in a deeper water regime as evidenced by a stratigraphic position transitional between thin-bedded iron-formation and overlying black shale; yet it contains primary hematite.

Sedimentological parameters imply that Unit A was deposited during two transgressive-regressive cycles in a basin with a strandline to the west and deeper water to the north and east. Well-rounded grains of terrigenous quartz, which persist throughout lithotopes 1-5, imply that much of the sedimentation occurred relatively close to the strandline.

Although Unit A in the Emily district has many mineralogical, textural, and chemical attributes indicative of "ordinary" iron-formation, it locally contains manganese oxides in amounts 10 to 100 times greater than the norm of 0.6 to 0.8 percent in the Biwabik Iron Formation (Morey and Morey, 1990). Manganese oxides occur principally in lithotopes 1-5 as disseminated grains, as thin pods or lenses, and as layers as thick as 1.5 meters that typically contain about 10 percent Mn; some contain as much as 20-30 percent Mn. Manganese oxides are particularly abundant near Ruth Lake where two laterally persistent zones about 15 to 18 meters thick have manganese tenors enriched to the 10-50 percent range. Both zones more or less coincide with stratigraphic positions occupied by the oolitic-pisolitic lithotope. They contain various proportions of psilomelane and cryptomelane, as well as hematite and quartz. Goethite and manganite may be locally abundant; where they occur, they are secondary phases that formed during a period of intense chemical weathering that modified these rocks in Late Jurassic or Early Cretaceous time.

The manganese oxides are most likely epigenetic in origin. They are confined to the porous and permeable parts of Unit A; rocks with the greatest primary porosity—such as quartz arenitic rocks in the epiclastic lithotope and the oolitic-pisolitic lithotope—have the most manganese. Morey and others (1991) have suggested that the manganese was deposited by a refluxing process involving reducing solutions that leached manganese from older rocks of the North range. The manganese was subsequently precipitated where the reducing solutions came into contact with oxidizing conditions in the depositional basin just below the sediment-water interface. Much of the manganese must have been precipitated early in the diagenetic history of the iron-formation, because texturally it occupies pore spaces normally filled with silica cement.

Mesozoic weathering of the rocks caused some redistribution of manganese. The abundance of manganese makes the Ruth Lake area in the Emily district a potential target for in-situ mining techniques currently being developed by the U.S. Bureau of Mines and the Mineral Resources Research Center of the University of Minnesota.

This project was supported in part by the basic research component of the Minerals Diversification Program, administered by the Minerals Coordinating Committee for the Minnesota State Legislature.

REFERENCES CITED

- Chandler, V.W., and Malek, K.C., 1991, Moving-window Poisson analysis of gravity and magnetic data from the Penokean orogen, east-central Minnesota: *Geophysics*, v. 56, p. 123–132.
- Morey, G.B., and Morey, P.R., 1990, Major and minor element chemistry of the Biwabik Iron Formation and associated rocks, Minnesota, in *AIME, Minnesota Section, 163rd Annual Meeting, and Mining Symposium, 51st, 1990, Proceedings: University of Minnesota, Duluth, Continuing Education and Extension, Center for Professional Development*, p. 259–287.
- Morey, G.B., Southwick, D.L., and Schottler, S.P., 1991, Manganiferous zones in the Early Proterozoic iron-formation in the Emily district of the Cuyuna Iron Range, east-central Minnesota: *Minnesota Geological Survey Report of Investigations 39*, 42 p.
- Southwick, D.L., Morey, G.B., and McSwiggen, P.L. 1988, *Geologic map (scale 1:250,000) of the Penokean orogen, central and eastern Minnesota, and accompanying text: Minnesota Geological Survey Report of Investigations 37*, 25 p., 1 pl.

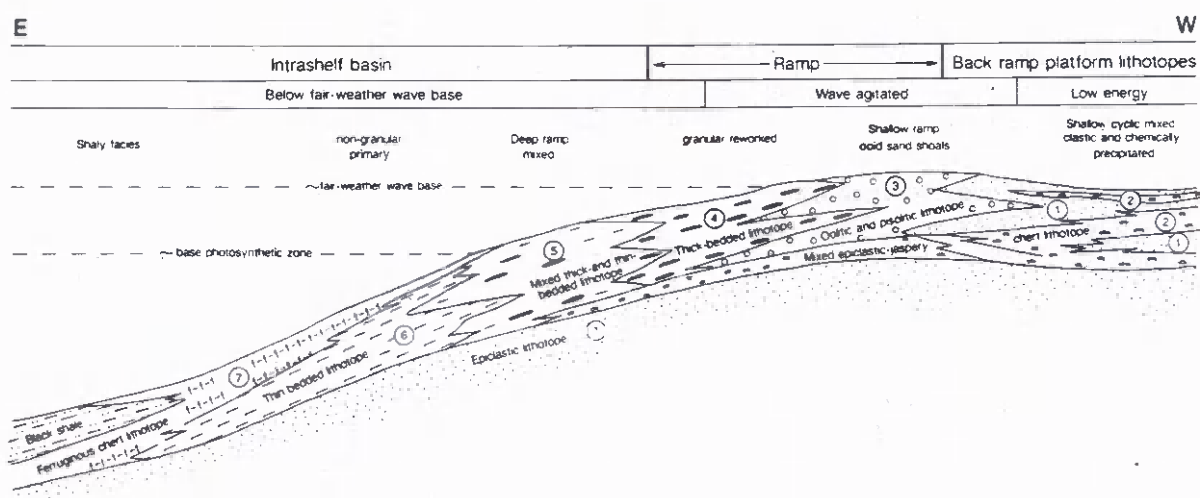


Figure 1. Schematic profile of lithotopes in the Emily district. No vertical or horizontal scale intended. Environmental nomenclature is typical of that used in Phanerozoic limestone-shale sequences.

PICK LAKE ZINC-COPPER-SILVER DEPOSIT

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The Pick Lake massive sulphide deposit is situated 20 km north of Schreiber, 145 km east of Thunder Bay, Ontario and 1.5 km from Minnova's Winston Lake mine.

The deposit occurs 1000 meters stratigraphically below the Winston Lake deposit at the base of a sequence of calc-alkalic volcanics and sediments. First indications of the deposit came in 1984 when Minnova drill tested a weakly mineralized horizon within a zone of strong hydrothermal alteration. Drill hole WL-9 intersected 0.3 meters of massive pyrrhotite within a thick sequence of altered clastic sediments and intermediate to felsic ash which was weakly mineralized with zinc. Subsequent drilling down dip led to the discovery of thin but high grade massive sulphides.

Exploration drilling has continued to systematically test the Pick Lake deposit at depth and has defined a steeply plunging sheet with a strike length of 400 meters, dip length of 1400 meters but an average thickness of less than 2 meters. In 1990, drill hole WL-67 intersected 13.4 meters of massive sulphides grading 2.6% Cu, 26.0% Zn and 106 g/t Ag at a vertical depth of 1050 meters. Drilling to date at Pick Lake totals 27,000 meters over 36 holes.

Core and poster display:

- regional geological map of N. W. Ontario
- geological map of the Winston Lake property
- 1:2000 composite section (Pick Lake stratigraphy)
- 1:2000 longitudinal section (Pick Lake deposit)
- surface geology map of the Anderson showing (Pick Lake)
- core representative of the fringe mineralization
- core representative of thin massive sulphides
- massive sulphide intersection WL-67
- sample suite of Pick Lake stratigraphy

PLATINUM GROUP ELEMENT POTENTIAL OF
KEWEENAWAN INTRUSIVE ROCK IN WISCONSIN

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ABSTRACT

Whole rock analyses of platinum in the Round Lake Intrusion, Sawyer County, Wisconsin discloses platinum enrichment with increasing iron and titanium accompanied by decreasing paladium. Anomalous chromium and vanadium also correlate with iron and titanium.

The Round Lake Intrusion is known only from boreholes and geophysical data. It is at least 8 km long and 22 km wide and is inferred to extend to a depth of 1400 m (Roder, 19773; Stuhr, 1976). Diabasic olivine gabbro and troctolite occur at the margin of an oxide-rich core of the trough-shaped intrusion. Dominant minerals are olivine, plagioclase and titanomagnetite in various proportions. In the core of the intrusion, olivine and plagioclase crystallized early and iron-titanium oxides crystallized late. The core of the intrusion consists of a magnetitite unit of 12 to 26 percent clusters of oxide and silicates, 9-15 percent olivine, 2-10 percent plagioclase, 54 to 72 percent titanomagnetite and less than 3 percent ilmenite. Plagioclase is An_{50} ; titanomagnetite averages $Mt_{50}Usp_{50}$ and contains 1.3 percent V_2O_3 . Commercial potential of the vanadium-rich core is limited because ilmenite-ulvospinel intergrowths are narrow, and ultra-fine grinding would be required for beneficiation. However, added values from platinum group elements may alter the economics.

		Pt ppb	Pd ppb	Co ppm	Cr ppm	V ppm
RL-01-0316	diabase	<5	38	35	35	408
RL-05-0557	dibase	7	103	28	94	478
RL-01-0324	diabase	8	41	29	50	391
RL-09-1190	lower magnetite/troctolite	11	1	54	349	609
RL-09-1179	lower magnetite/troctolite	30	3	105	790	1050
RL-01-0184	Magnetite/troctolite	75	3	155	541	na
RL-05-0320	magnetitite	106	4	142	2420	na
RL-02-0078	magnetitite	116	1	189	2530	na
RL-10-0386	magnetitite	120	5	170	2820	>2000

Stuhr, S.W., 1976, Geology of the Round Lake Intrusion, Sawyer County, Wisconsin: unpublished M.S. thesis, University of Wisconsin-Madison, 148 p.

Roder, D.L., 1973, The petrology and chemistry of the Round Lake Intrusion, Northwest Wisconsin: unpublished M.S. thesis, University of Wisconsin-Madison, 115 p.

The Porcupine Mountains area, Michigan - a Keweenawan central volcano?

by

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Although magmatism related to the Midcontinent rift system is mostly basaltic composition, intermediate and felsic rocks comprise about 10 to 15% of the volcanic section in the Lake Superior region. Locally, intermediate and felsic rocks dominate the volcanic suite, as they do in the Porcupine Mountains area of northern Michigan. The Porcupine Mountains area is anomalous in the Midcontinent rift system not only because of its abundance of felsic rocks but also because of the coincidence of two geophysical anomalies -- a gravity low and a magnetic low -- superimposed on a broader magnetic high (Fig. 1). In addition, the abundant rhyolite and intermediate rocks form a partial ring of topographic highlands making up the structurally complex and apparently folded felsic volcanic pile. For clarity, the entire area underlain by the elliptical broad magnetic high (and the corresponding topographic highlands) will be called the Porcupine Mountains volcanic center. Within this volcanic center, the Porcupine Mountains themselves make up the northern highlands, Porcupine Peak forms the western highlands, and the hills around the Bergland firetower make up the southeastern highlands (Fig. 1). Earlier workers suggested that this area is a remnant of an Icelandic-style central volcanic complex (White, 1972; Green, 1977; Kopydlowski, 1983), but evidence supporting this suggestion has been largely undocumented. To evaluate this hypothesis, mapping, geochemical, isotopic, and geophysical studies were recently undertaken in the Porcupine Mountains area.

Preliminary results of mapping and geophysical studies indicate many similarities between Icelandic central volcanoes and the inferred Porcupine Mountains volcanic center. For instance, the Porcupine Mountains center formed at the edge of an active rift zone and is about 30 to 40 km wide, comparable in size to Icelandic central volcanoes. Earlier workers recognized that an accumulation of felsic and intermediate rocks, called the "unnamed" formation, formed a lens-shaped body underlain by the northwest-dipping basalts of the Portage Lake Volcanics (Fig. 1). The "unnamed" formation is being formally named the Porcupine Volcanics (Cannon and Nicholson, in review). This formation is more than 2 km thick at its thickest but thins away from the Porcupine Mountains area. The thickness of the overlying Copper Harbor Conglomerate decreases substantially over the Porcupine Volcanics.

Recent mapping has shown that much rhyolite in the southern highlands occurs as subvolcanic bodies that intrude flows of intermediate composition. These rhyolites are commonly porphyritic, containing both quartz and feldspar phenocrysts. Near the top of the Porcupine Volcanics in the southern highlands, an extrusive rhyolite body contains mostly small feldspar phenocrysts. In contrast, most rhyolite bodies in the northern highlands are extrusive flows. However, these rhyolites are typically massive aphyric flows or they may contain only sparse feldspar $\pm$ quartz phenocrysts. Understanding the chemical relationships among the rhyolite bodies in the Porcupine Volcanics awaits the results of detailed geochemical studies.

Gravity modeling across the Porcupine Mountains volcanic center requires the presence of a felsic stock to account for the low gravity anomaly beneath the

volcanic center (Klasner and Jones, 1989). A felsic stock also is consistent with the coincident low magnetic anomaly (King, 1987). The geophysical inference of a felsic stock lying beneath the volcanic center supports the comparison with the Icelandic model of a central volcano overlying a shallow magma chamber.

Numerous faults and apparent folding complicate structural interpretation in this area. For example, in the northern highlands (in the Porcupine Mountains State Wilderness Area), a change in the dip of volcanic units from south to north led Hubbard (1975) to propose an anticline. However, detailed mapping indicates that some individual stratigraphic units cannot be traced across the proposed fold. An alternative model for the structure of the northern highlands is that different rhyolite bodies may represent individual small (1-3 km wide) flow-dome complexes, some with carapace breccias still intact, and possibly localized along a major caldera-bounding fault. Similar flow-dome complexes have been documented in the Torfajökull volcanic complex in Iceland (Macdonald et al., 1990). Thus, we suggest that the elliptical area of highlands and the coincident geophysical anomalies reflect the original shape of the volcanic shield, although it has been somewhat modified by post-rift compressional deformation.

The Porcupine Mountains volcanic center appears to share many similarities with Icelandic-style central volcanoes, but a more complete understanding of the area will require careful interpretation of structures along nearby seismic reflection profiles, detailed correlation of stratigraphic units and structural analysis within the center, and careful analysis of chemical, isotopic and volcanological data.

References

- Cannon, W.F., and Nicholson, S.W., in review, Revisions of stratigraphic nomenclature within the Keweenaw Supergroup of northern Michigan. U.S. Geological Survey, Bulletin 1970-A.
- Green, J.C., 1977, Keweenaw plateau volcanism in the Lake Superior region. Geological Association of Canada, Special Paper 16, p. 407-422.
- Hubbard, H.A., 1975, Geology of Porcupine Mountains in Carp River and White Pine quadrangles, Michigan. U.S. Geological Survey, Journal of Research, v. 3, p. 519-528.
- King, E.R., 1987, Aeromagnetic map of the Iron River 10 x 20 quadrangle, Michigan and Wisconsin. U.S. Geological Survey, Miscellaneous Investigations Series, I-1360-F, 1:250,000.
- Klasner, J.S., and Jones, W.J., 1989, Bouger gravity anomaly map and geologic interpretation of the Iron River 10 x 20 quadrangle, Michigan and Wisconsin. U.S. Geological Survey, Miscellaneous Investigations Series, I-1360-E, 1:250,000.
- Kopydlowski, P.J., 1983, The Oak Bluff Volcanics, a Middle Keweenaw central volcano; Porcupine Mountains region, Michigan. unpublished M.S. thesis, Michigan Technological University, Houghton, 88 pp.
- Macdonald, R., McGarvie, D.W., Pinkerton, H., Smith, R.L., and Palacz, Z.A., 1990, Petrogenetic evolution of the Torfajökull volcanic complex, Iceland I. Relationship between the magma types. Journal of Petrology, v. 31, p. 429-459.
- Walker, G.P.L., 1963, The Breiddalur central volcano, eastern Iceland. Quarterly Journal of the Geological Society of London, v. 119, p. 29-63.
- White, W.S., 1972, The base of the Upper Keweenaw, Michigan and Wisconsin. U.S. Geological Survey Bulletin 1354-F, 23 pp.

PHYSICAL VOLCANOLOGY OF THE FOOTWALL
ROCKS AT THE WINSTON LAKE MASSIVE SULFIDE DEPOSIT

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Footwall rocks at the Winston Lake massive sulfide deposit consist of an amphibolite grade, hydrothermally-altered sequence of north-south trending volcanic and volcanoclastic rocks. Geological mapping, drill core, and petrographic studies allow detailed subdivision and volcanological analysis of the stratigraphy.

Thick (100-325m), massive to poorly-bedded mafic to felsic volcanoclastic rocks form the base of the stratigraphy and are bounded to the west by granitic intrusive rocks. Intercalated felsic pyroclastic rocks form marker horizons and suggest the deposits thicken southward.

The clastic rocks are overlain to the east by 100-850m of interlayered felsic and mafic lava flows which, in general, thicken southward. Felsic flows, which constitute 80% of the succession, are quartz-feldspar-phyric, massive, and rarely flow-banded and brecciated. Mafic lava flows vary from massive to well-pillowed, and aphyric to feldspar-phyric. Local mafic and felsic dikes are present near the south end of the sequence and are thought to represent feeders to the lava flows.

Immediately above the lava flows is a 75-200m thick sequence of pyroclastic and volcanoclastic rocks. Pumice-bearing felsic pyroclastic rocks predominate to the north with pumice size and content increasing northward. The pyroclastic rocks interfinger to the south with mafic-felsic volcanoclastic rocks. The volcanoclastic rocks are locally transected by a laterally limited (100-125m), but thick (150m), succession of aphyric mafic lava flows, sills, and dikes. The mafic rocks are thought to fill an axial trough, and to represent a feeder complex to lavas higher in the section. The flows vary from massive to pillowed; peperites and cm-scale sheet flows are locally well-developed.

The Winston Lake Horizon caps the footwall sequence and consists of 3-4 interlayered mafic lava flows and mafic-felsic volcanoclastic rocks and cherty tuffs. The lavas are aphyric, laterally extensive (>2km), and thicken (2-80m) southward. Volcanoclastic rocks and tuffs vary from 1-20m in thickness and are massive to well-laminated.

The stratigraphy at Winston Lake developed with cyclic accumulation of volcanoclastic and volcanic rocks; lava flows were derived from a rift-related southward source. In contrast, felsic pyroclastic rocks appear to have been derived from an unrelated northward source. The lack of hydrovolcanic or vesicular deposits suggests deep water volcanism prevailed at Winston Lake.

THE NEDA IRON FORMATION -- A PRODUCT OF VULCANISM?

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The Neda iron formation crops out along the east, south, and southwest flanks of the Wisconsin Arch (Fig. 1). It lies at the top of the upper Ordovician Maquoketa shale and is overlain by Silurian Mayville dolomite. The formation is discontinuous. It reaches a maximum thickness of about 12 meters. Down dip, away from the arch, its extent is not well known.

The Neda is characterized by an abundance of oblate spheroidal structures not more than about 2 mm in diameter. These have generally been described as ooids, implying that they originated by wave and current action on the sea floor.

Near the village of Neda in eastern Wisconsin, the type locality, the formation was formerly mined in small open cuts and shallow underground workings. Two types of ore were recognized: "soft ore," in which the "ooids" are weakly cemented together, and "hard ore," in which they are well cemented. Hard ore occurs as a capping on the soft ore. It is generally not more than a meter thick.

My ideas concerning the origin of the Neda formation are based mainly on petrographic examination of a few thin sections of hard ore from the type locality. Lakeside 70 was used to attach the rock to the slide. This cement, unlike epoxies, does not gelatinize in acids. By soaking the section for several days in strong (6N) nitric acid I got rid of most of the hematite and limonite which makes an untreated section largely opaque. Removal of these ingredients did not leave holes in the section. It appears that the iron oxide minerals are finely disseminated through the host materials in which they occur.

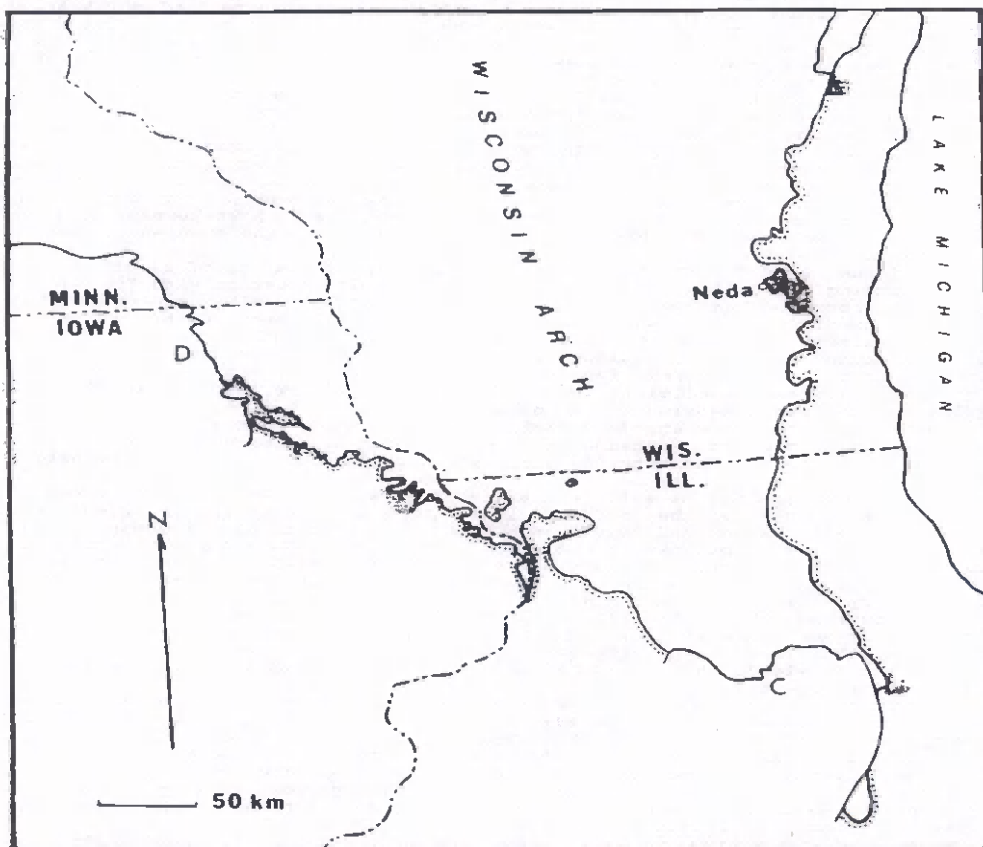


Fig. 1 Outcrop of Ordovician-Silurian boundary in parts of Minnesota, Iowa, Illinois, and Wisconsin. Dots are on the down-dip side of the line. Areas where Neda formation is exposed are stippled. The Ordovician-Silurian boundary is overlain in places by post-Silurian sediments: D - Devonian; C - Carboniferous. Geology, except Neda areas, from U.S. Geological Survey, Geologic Map of the United States, 1/250,000, 1932.

So far as I am aware, very little work has been done on thin sections of the Neda formation from which most of the iron oxides have been removed. Most workers have contented themselves with the examination of polished surfaces or acetate peels. A rather detailed study of the mineralogy of the Neda formation at Neda was published in 1934 by Hawley and Beavan (1). They worked mainly with crushed material obtained from a mining company -- presumably a mixture of hard and soft ore. Thin fragments were cleared of hematite and limonite by soaking them in a combination of nitric and hydrochloric acid, then examined by transmitted light under a petrographic microscope. If the identification of a mineral by petrographic methods was uncertain, and the mineral seemed important, they checked it by powder X-ray diffraction.

In the hard ore from Neda, the "ooids" alone are so varied and complex that it is not easy to draw conclusions about their origin. I am convinced, however, that they were not formed by sedimentary processes and are therefore not ooids in the usual sense of the term. It seems to me more likely that they are miniature accretionary lapilli of volcanic origin. A volcanic origin is suggested by Hawley and Beavan's observation that "the most abundant transported fragments in the ore are rough, angular grains of scoriaceous lava." They also observed that the lava, when cleared of iron oxides, is a "dirty, green to brown volcanic glass." I found fragments of what I take to be volcanic glass mainly as nuclei in "ooids." They are not scoriaceous and it is open to question whether they are really glass or some amorphous or submicroscopically crystalline material which may have been derived from glass.

Where did this glass come from and how old is it? Hawley and Beavan reject the idea that it came from nearby volcanoes which were active when the Neda formation was deposited. They prefer a Precambrian source to the "west or northwest" from which the glassy fragments were transported by streams or marine currents. Their objection to a nearby, contemporary source is that "as yet no igneous activity of such age is recognized in this part of North America." I think there is a much more serious objection to their proposed alternative. The youngest Precambrian volcanics to the west (along with axis of the Wisconsin Arch) and northwest (the present Lake Superior region) are Keweenaw. Only a very small percentage of whatever glass may originally have been present in the Keweenaw volcanics is likely to have escaped devitrification as early as Ordovician-Silurian time. Even if we assume that there was more glass in the Keweenaw Volcanics than there is now, how could transported fragments of it remain apparently unaltered in the Neda formation while, in the source area, alteration was actively progressing? One may also ask why, in the Neda formation, glassy fragments should be abundant while fragments of crystalline lava, which certainly would have been more abundant in the source area, are missing. Igneous activity of Paleozoic or later age may not have been recognized in the area where the Neda formation was deposited in Hawley and Beavan's day but now we have the Lake Ellen kimberlite to remind us that there has, in fact, been post-Keweenaw volcanic activity south of Lake Superior. Whether it extended down into the area where the Neda was deposited remains to be seen.

Most of the "ooids" in my thin sections show a thick coating of slightly anisotropic material surrounding any nucleus that may be visible. This, together with the nucleus, may be regarded as the "core" of the "ooid." In "ooids" which lack a visible nucleus, the core consists entirely of the nearly isotropic material. Most of it is pale green or brown. There is evidence that the brown variety was formed by oxidation of the green. Both varieties show imperfect concentric lamination around the nucleus, if one is visible -- otherwise around what may be taken roughly as the center of the core. The laminae are most clearly visible XN. Light passing through them is polarized parallel to the long dimensions of the laminae (and also, of course, at right angles to the long dimensions). My guess is that this is a result of strain in otherwise isotropic material. There are abundant small inclusions which look as if they may be particles of volcanic ash, also platy or lath-shaped crystals which are elongated parallel to the long dimensions of the laminae. The material which forms cores also occurs in alternate shells around the cores.

The same question may be asked concerning this slightly anisotropic core material as was asked about certain nuclei in the "ooids": is it glass or some amorphous or submicroscopically crystalline material? Hawley and Beavan identified the material of which many shell fragments they observed consisted as halloysite. According to Ross and Kerr (2), halloysite is a submicroscopically crystalline clay mineral related to kaolinite. If the green or brown core material which I observed is halloysite, it has presumably been weathered. The material weathered may very well have been volcanic glass. I suggest that the material forming cores in the "ooids" I observed, and shells separated from the cores but composed of the same material, were formed by the accretion of tiny droplets of liquid lava onto nuclei which, in some cases, are visible; in others, not. The droplets, I think, spread out over the rounded surface of previously accreted material which had had time to harden or become extremely viscous. Thus the imperfect lamellae were formed.

Alternating with the shells of green or brown core material are shells composed of material which is transparent and colorless. It is generally completely isotropic but may contain very small, nearly equidimensional crystals showing low birefringence. The refractive index I found to be close to 1.54, a little lower than the mean refractive index of core material. Opaque patches of iron oxide minerals are commonly present in it. Scattered reflected light from these patches makes a good deal of the adjoining clear material look tomato-red XN. Hawley and Beavan identified the material which they found in transparent, colorless shells as opal. They too found that it has a refractive index of about 1.54.

The mode of deposition, or emplacement, of the colorless transparent shells seems to have been rather extraordinary. Some of these shells were originally composed of relatively large crystals, now pseudomorphs. Euhedral outlines of these crystals may be seen projecting from the inner and/or outer surfaces of shells composed of them. In one case which I observed a shell of this type pinches out and a single, isolated, euhedral crystal of the same material is present in core material a short distance beyond its tip. I see this as evidence that the shell was growing toward the isolated crystal, which is in line with it. What controlled the direction of growth is uncertain. Transparent, colorless shells roughly parallel the lamellae in adjacent core material. This means that they also parallel the outer surfaces of the core and of the "ooid" as a whole. Possibly more or less evenly spaced zones of tension developed in core material of

which the "ooid" seems originally to have been entirely composed. If these zones of tension were due to shrinkage as a result of either cooling or dehydration it is to be expected that they would parallel the outer surface of the "ooid."

Many of the colorless, transparent shells show no pseudomorphs of antecedent crystals and were presumably amorphous or submicroscopically crystalline from the start. Some shells of this type are clearly composites made up of many very thin shells in contact with each other. This may be the result of deposition in a crack, which opened, was filled, and then reopened several times.

I am doubtful about the idea, embraced by other workers, that the oblateness of the "ooids" in the Neda formation is due to compression under the load of overlying sediments. The soft ore contains cylindrical structures a few cm in diameter which appear to be masses of material, mud-like in consistency, which rolled down an inclined depositional surface, picking up additional material as they progressed. "Ooids" in these structures are flattened tangentially, indicating that the flattening took place before overlying sediments were deposited. If so, the most likely cause of the flattening would be rapid rotation while the "ooids" were still soft and airborne.

Kimberlites and kimberlitic ejecta contain spheroidal bodies 1-10 mm in diameter known as "pelletal lapilli." In these, some kind of a nucleus--usually a mineral grain--is surrounded by very fine-grained, optically unresolvable, material. The latter often exhibits a poorly defined concentric structure and contains platy or lath-shaped minerals with their long dimensions parallel to the concentric layering, if this is present; otherwise parallel to the surface of the lapillus. Clement (3) originally explained these bodies as quenched lava droplets. This does not account for their concentric structure, however. I attribute the concentric structure in core material of Neda "ooids" to accretion. Clement (4) later suggested that accretion may also be responsible for the concentric structure in pelletal lapilli of kimberlites. It is not clear whether the rapid rotation postulated to account for the oblateness of Neda ooids and also numerous pelletal lapilli was in progress during accretion or was somehow initiated after accretion had ended.

In comparing certain features of Neda "ooids" with those of pelletal lapilli I do not mean to imply that the volcanic activity which, in my opinion, produced the Neda formation was the same as, or similar to, that which produces kimberlites. This is not an impossibility, however.

Many "ooids" in the Neda hard ore show evidence of deformation after the rigid clear shells had been emplaced but before core material had completely solidified. This caused fragmentation of the clear layers and displacement of the fragments, accompanied by flowage of core material. Possible causes of deformation are (1) shock of landing; (2) impact by a later arrival after landing; (3) viscous flow of the accumulated "ooids" and matrix; (4) compression under the load of overlying sediments. Where deformation decreased the volume of an "ooid" core material was squeezed out into the surrounding matrix.

Many workers have observed fragments of fossils, sand grains, and pieces of pre-existing "ooids" serving as nuclei in Neda "ooids." These occurrences appear to support the concept of a sedimentary origin, rather than a volcanic one. I suggest, however, that a volcanic crater near sea level may be filled, during intervals of quiescence, by sea water and that normal marine sediments containing the remains of organisms may be deposited in it. Accretionary lapilli will fall inside, as well as outside of, the crater when an eruption occurs. Fragments of these lapilli, the sediments, and hard parts of organisms all may be blown aloft by a subsequent eruption.

It does not seem likely, to me, that the Neda formation was deposited under water. If the fluidity of core material in "ooids" and the matrix was due to high temperature, as I propose, an aquatic environment of deposition is ruled out because it would have caused rapid cooling. I think that deposition took place on land -- land which, to allow for occasional flooding of the crater of the source volcano, was not far above sea level.

I have looked at a good deal of the matrix surrounding "ooids" in my thin sections. It contains many angular fragments, mostly opaque, which may be bits of volcanic glass replaced by iron oxides. Hawley and Beavan saw a lot of these, too. However, the fragments they saw were scoriaceous; the ones I saw are not. There are other inclusions of many kinds. They are imbedded in what appears to have been fluid or plastic material, kept so by high temperature in my opinion. After hardening, a good deal of deuteric (?) replacement seems to have occurred. I shall not attempt further description and interpretation of the matrix. My main purpose here is to promote the theory of volcanic origin, and I think it is sufficiently promoted by consideration of the "ooids" alone.

REFERENCES

- (1) Hawley, J. E., and A. P. Beavan. 1934. "Mineralogy and Genesis of the Mayville Iron Ore of Wisconsin," *American Mineralogist*, Vol. 19, p. 493-514.
- (2) Ross, C. S., and P. F. Kerr. 1934. "Halloysite and Allophane," U. S. Geological Survey, Professional Paper 185-G, p. 135-148.
- (3) Clement, C. R., 1973. "Kimberlites from the Kao Pipe, Lesotho." *Lesotho Kimberlites*, p. 110-121.
- (4) Clement, C. R., 1982. "A Comparative Geological Study of Some Major Kimberlite Pipes in the Northern Cape and Orange Free State." Ph.D. thesis, Univ. of Cape Town.

LITHOGEOCHEMISTRY AND GEOLOGICAL MAPPING IN THE VERMILION GREENSTONE BELT, MINNESOTA, AS AN AID TO MINERAL EXPLORATION

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The Vermilion greenstone belt in northern Minnesota is a complex tectonic assemblage of late Archean volcanic and sedimentary rocks that consists of the classic Vermilion district, where iron ore has been mined for more than a century, and its subsurface extensions to the west beneath the glacial cover. Several cycles of mineral exploration for commodities other than iron have occurred in the belt over the years, generally without success; perhaps the most intensive of these has been in the last decade, following the general recognition that the Vermilion greenstone belt is tectonically a part of the very productive Shebandowan-Wawa-Abitibi subprovince of the Superior province of Canada. To assist industry with the difficult task of conducting exploration in this poorly exposed region of Minnesota, the State has conducted regional mapping projects aimed at providing the geological, geophysical, and geochemical framework required for mineral potential assessment and strategic planning. The lithogeochemistry and mapping project described here is designed to provide regional data on rock compositions within the Vermilion greenstone belt.

Recent geological mapping, supported by detailed aeromagnetic mapping and shallow drilling in poorly exposed areas, has led to the recognition of at least three volcanic-sedimentary cycles in the Vermilion greenstone belt. These are: (1) a dominantly calc-alkaline sequence that includes rocks south of the Mud Creek and Wolf Lake faults in the Vermilion district and southeast of the Bear River fault in northeast Itasca County; (2) a dominantly tholeiitic sequence that includes rocks north and northwest of these faults; and (3) a mixed volcanic sequence (calc-alkaline and tholeiitic) of unknown stratotectonic affinity (in the "Virginia horn") that lies south of sequence (1) and is separated from it by intrusive granitic rocks of the Giants Range batholith.

Approximately 280 rock samples have been collected from these three volcanic sequences and analyzed for major elements, minor elements, and trace elements (70 elements total). These data form an analytically consistent set that characterizes the lithogeochemistry of the volcanic sequences and facilitates comparisons, correlations and petrochemical interpretations of them. The data also provide the statistical background on the distribution of metal background concentrations, and pathfinder elemental associations in the rocks that is necessary for meaningful interpretation of the more than 6,200 partial rock analyses that have accumulated over the past century from academic and exploration activities in the Vermilion greenstone belt.

Products of the lithogeochemistry project will be: (1) a generalized regional geologic map of the central part of the Vermilion greenstone belt that shows sample locations for the 280 new 70-element rock analyses; (2) a computer file (electronic) of the new analytical data; (3) a computer file (electronic) of the archival analytical data; and (4) a report that describes methodologies and provides interpretations.

THE NATURE AND SOURCE OF MIDCONTINENT RIFT IGNEOUS ROCKS

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Trace element and Nd-Sr isotopic data indicate that the Keweenawan Midcontinent Rift igneous rocks originated from both mantle and crustal sources with mafic rocks being derived from the mantle and more felsic rocks being derived from the crust. The Mineral Lake intrusions near Mellen, Wisconsin, illustrate the occurrence of interlayered mafic and felsic intrusions with mixed mantle and crustal origins. The bimodal source of Midcontinent Rift igneous rocks explains the bimodal compositional distribution of these and other flood basalt province rocks.

Nd-Sr isotopic data for Midcontinent Rift igneous rocks (Brannon, 1984; Dosso, 1984; Paces and Bell, 1989) plot in three largely separate fields on an Nd-Sr(T) diagram with $T = 1100$ Ma, suggesting limited mixing and contamination. The three fields represent a mafic rock mantle field surrounding Nd-Sr values of zero, and lower and upper crustal fields for more felsic rocks. The Mineral Lake mafic rocks plot in the field defined by other Midcontinent Rift mafic rocks indicating an origin from slightly depleted or near chondritic mantle. The Mineral Lake felsic rocks fall close to the crustal fields defined by other Midcontinent Rift felsic rocks. Some mixing is indicated by the narrow isthmus connecting the mafic mantle field with the more felsic lower crustal field.

Spider diagrams of trace element data for the Mineral Lake mafic rocks relative to the calculated field for flood basalts (Thompson et al., 1984) indicates that the mafic rocks, and perhaps other Keweenawan mafic rocks, are contaminated. Consequently, the Mineral Lake mafic rocks are derived from slightly depleted mantle contaminated with crustal material. Similar plots for the Mineral Lake felsic rocks indicates they are similar to felsic rocks with a mixed mantle and crustal origin on the basis of isotopic evidence (Thompson et al., 1984). The felsic melts were probably generated by heat from upwelling mantle melts of the type which produced the mafic intrusion and followed channels opened by earlier fast moving mafic magmas.

REFERENCES

- Brannon, J. C. (1984) Geochemistry of successive lava flows of the Keweenawan North Shore Volcanic Group. Ph.D. dissertation, Washington University, St. Louis.

- Dosso, L. (1984) The nature of the Precambrian subcontinental mantle. Isotopic study (strontium, lead, neodymium) of the Keweenaw volcanism of the north shore of Lake Superior. Ph.D. dissertation, University of Minnesota, Minneapolis.
- Paces, J. B. and Bell, K. (1989) Non-depleted sub-continental mantle beneath the Superior Province of the Canadian Shield: Nd-Sr isotopic and trace element evidence from Midcontinent Rift basalts. *Geoch. Cosmoch. Acta*, 53, 2023-2035.
- Thompson, R. N., Morrison, M. A., Hendry, G. L. and Parry, S. J. (1984) An assessment of the relative roles of crust and mantle in magma genesis: an elemental approach. *Phil. Trans. Roy. Soc. London A*, 310, 549-590.

CORRELATION OF IGNEOUS UNITS
AT THE MINNAMAX DEPOSIT, NE MINNESOTA

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The Minnamax Cu-Ni Deposit (Babbitt Deposit) is situated within what has been informally referred to as the Partridge River intrusion of the Duluth Complex (1.1 Ga), northeastern Minnesota (Figure 1). Within the deposit are a wide variety of troctolitic, ultramafic, and footwall rock types, and hornfelsed inclusions (both sedimentary and igneous(?)). Many specific rock types are correlative between drill holes and can grossly be categorized into seven subhorizontal troctolitic units, three types of hornfelsed inclusions, and a late cross-cutting pegmatitic phase. Also present are correlative units within the footwall rocks. These correlative rock units were identified by detailed relogging of 61 drill holes (117,605' of core) and are portrayed on nine cross-sections through various portions of the deposit.

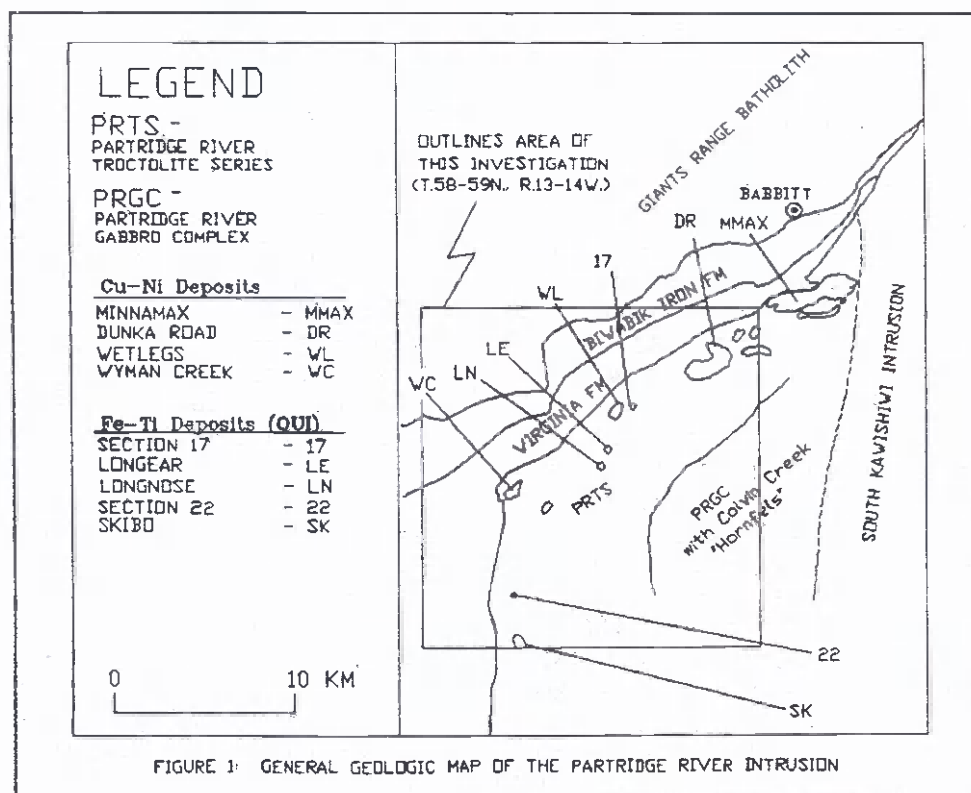
Most of the rock units defined at the Dunka Road Cu-Ni Deposit (located to the immediate SW of Minnamax) by Severson and Hauck (1990) are present at Minnamax. However, the overall picture at Minnamax is somewhat more complicated than Dunka Road due to rock type changes that are manifest by: 1) pinch-out and reappearance of specific marker-bed units, 2) down-strike gradational changes of ultramafic horizons, 3) extremely limited areal extent of some ultramafic horizons, and 4) gradational changes in the troctolitic rock types between any two drill holes. In some areas a particular marker horizon may "disappear" and be replaced by another marker horizon, which in turn, may "disappear" laterally. In spite of these local difficulties, a gross stratigraphy of seven horizontal igneous units (Figure 2) are present at Minnamax and consist of (from bottom to top): Unit I - heterogeneous, sulfide-bearing augite troctolite and troctolite with abundant sedimentary inclusions; Unit II - homogeneous troctolites with a basal picrite horizon (II is present only in SW Minnamax); Unit III - mottled anorthositic troctolite to augite troctolite with characteristic olivine oikocrysts (III is present mainly in SW Minnamax and is enveloped by Unit I to the NE); Unit IV - mixed troctolite and augite troctolite (at the base or top of Unit IV in two different areas) with a basal ultramafic horizon ("± picrite"); Unit V - homogeneous anorthositic troctolite (gradational contact with Unit IV); and Units VI and VII - homogeneous troctolites with basal ultramafic horizons (more abundant and thicker ultramafic horizons in the Bathtub cross-section). Specific marker horizons utilized in drill hole correlations include (Figure 2): Unit III, "± picrite", "pocket picrite", top of Unit IV (augite troctolite), and the base of Units VI and VII. The troctolitic rock units are commonly cut by thin granophyric veins, hybrid hornblendite bodies, and pegmatitic pyroxenite bodies (OUI -oxide ultramafic intrusions). Chlorine-rich drops which coat the core surface are common in the OUI and ultramafic horizons.

Several enigmatic hornfelsed inclusions are present in Units VI and VII at Minnamax. These are grouped in two categories which include: 1) granular gabbro to olivine gabbro which contain crude ovoid-shaped plagioclase-filled zones (vesicles?), and 2) granular oxide-rich olivine gabbro which also contains plagioclase-filled ovoids and modally bedded magnetite (± hercynite). The later inclusion type megascopically resembles the material present within the Colvin Creek "Hornfels" area (5 miles SW of Minnamax). While these two inclusion types are readily correlative between drill holes, their exact nature remains unknown.

Interestingly, modally bedded magnetite is also present in picritic horizons which occur at the same stratigraphic levels as the second inclusion type.

Another enigmatic rock type is present within the lower 50-100' of the Virginia Formation footwall rocks. This rock is generally concordant with the overall bedding trend, exhibits a gradational(?) contact with the surrounding sedimentary rocks, and generally exhibits a granoblastic texture; the massive sulfide ore is restricted to the rock types above this horizon. Preliminary petrography and geochemistry indicate that this horizon contains hornblende and olivine (serpentinized), high Cl contents (up to 1300 ppm) and high MG Numbers (10-20) which are similar to values within ultramafic horizons, and high Cr contents (800-2300 ppm) which are much higher than anything sampled within the overlying troctolitic rocks. These data infer that this horizon may represent either a metamorphosed early Keweenaw sill (chilled material?) or a metamorphosed mafic flow within the Virginia Formation -- further study on this horizon is pending.

Severson, M.J., and Hauck, S.A., 1990, Geology, geochemistry, and stratigraphy of a portion of the Partridge River intrusion, northeastern Minnesota: Natural Resources Research Institute, Technical Report, NRRI/GMIN-TR-89-11, Duluth, Minnesota, 240 p.



PARTRIDGE RIVER INTRUSION

15 MILES

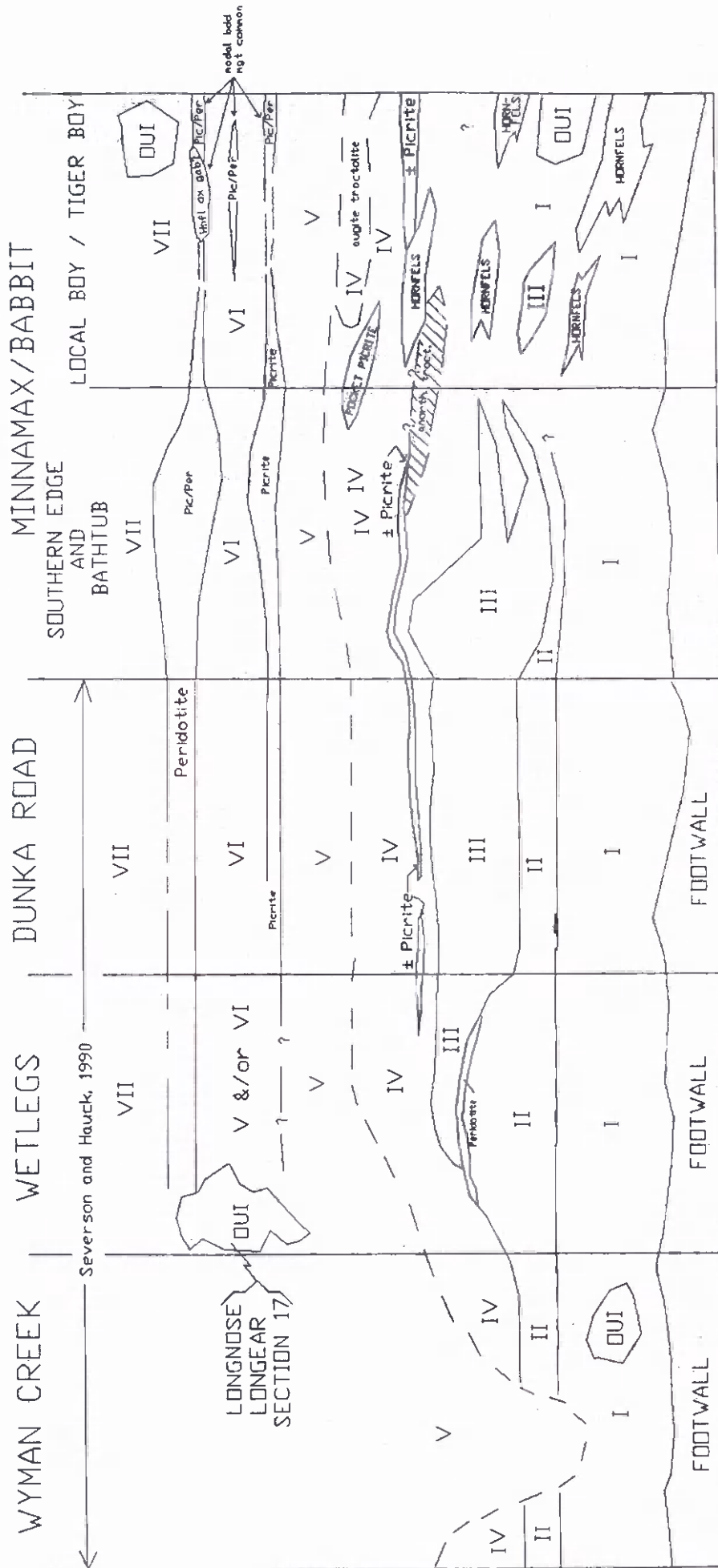


FIGURE 2: Strike-length correlation of major igneous units within the basal 3000 ft. of the Partridge River intrusion.

THREE-DIMENSIONAL MODELLING OF THE MAGNETIC ANOMALY - CENTRAL LAKE SUPERIOR

D. Teskey

ABSTRACT

Two and one-half dimensional modelling of the central portion of Lake Superior has been carried out using the high resolution aeromagnetic data collected by the GSC's Queenair aircraft in 1987 for the Great Lakes International Multidisciplinary Program on Crustal Evolution (GLIMPCE). Individual 2.5 dimensional models for profiles spaced approximately 10 km apart can be combined using trigonal surfaces to produce 3 dimensional models. These models indicate up to 40 km of volcanic flows, with the lower members having reversed magnetization, similar to the lower Osler group. These models tend to agree with the interpretation of the seismic profiles shot in 1986 as part of the GLIMPCE program.

MIDCONTINENT RIFT STRUCTURE INTERPRETED FROM
THE GNI/ARGONNE SEISMIC DATA SET

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Midcontinent rift structure is interpreted from 2500 km of orthogonally-oriented seismic profiles located in Lake Superior to have evolved in the following sequence: A) Localized volcanic-filled basins first developed (Hinze et al., 1990) and later coalesced to form the main axial rift basin. Volcanic flows extruded at this time are constant in thickness, suggesting that the major component of rift subsidence began after development of the primary axial basin. B) The main rift stage involved crustal extension, subsidence, and rapid lava extrusion. Lava flows interpreted as Portage Lake and Osler equivalents exhibit a pronounced fanning geometry towards the rift's axis, indicating extrusion into a rapidly subsiding basin. C) Volcanic cessation is marked by a region-wide mixed sediment-volcanic facies that separates a lower, dominantly volcanic sequence from an upper sedimentary series. D) Post-volcanic sedimentary basins developed, reaching thicknesses of 7 km, or more. E) Sediment basin development was interrupted by a compressional event that reactivated the normal boundary faults, producing high-angle reverse and thrust faults. Faulting and folding involved all of the volcanics and the older Oronto group sediments. F) A regional unconformity developed and is overlain by the youngest Keweenaw-age sediments.

The geometry and location of several major faults is clearly detailed by the seismic data set. A southeast extension of the Keweenaw Fault from the Keweenaw Peninsula is strongly corroborated. The Douglas Fault must parallel the southern shoreline, juxtaposing its southern dip against the Keweenaw Fault's northward dip, and probably dies out near the Porcupine Mountains. Ebinger (1989) described a similar fault geometry in the Western Rift System of East Africa. A shear fault or accommodation zone is imaged on the northeast side of White Ridge, which acts to separate a dominantly thrust fault regime to the northeast from the high-angle reverse faults observed on White Ridge.

Synthesis of the structural features imaged by the seismic profiles suggests that crustal shortening was directed NW-SE in western Lake Superior and NE-SW in the eastern lake. A net N-S

component of crustal shortening, as argued by Cambray (1988), could explain the fault and fold geometries observed throughout the lake. The Keweenaw Volcanics behaved as a single "thrust" sheet in the western lake, overriding a basal decollement between Animikie and pre-Portage Lake Volcanic units. Tilted, folded, and uplifted volcanic units imaged in the eastern lake also support this "thrust" sheet interpretation.

REFERENCES CITED

Cambray, F.W., 1988, A Tectonic Model for the Mid-continent Rift System: Abstract Volume, 34th Institute on Lake Superior Geology, Marquette, MI, p. 17.

Ebinger, C.J., 1989, Geometric and Kinematic Development of Border Faults and Accommodation Zones, Kivu-Rusizi Rift, Africa, TECTONICS, v.8, no.1, pp. 117-134.

Hinze, W.J., L.W. Braile, and V.W. Chandler, 1990, A Geophysical Profile of the Southern Margin of the Midcontinent Rift System in Western Lake Superior, TECTONICS, v.9, no.2, pp. 303-310.

REGIONAL STRATIGRAPHIC MODEL OF LATE CRETACEOUS SEDIMENTS AND THEIR
RELATIONSHIP WITH THE UNDERLYING PRE-LATE CRETACEOUS WEATHERING PROFILE
ALONG THE MINNESOTA RIVER VALLEY, MINNESOTA.

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The presence of pre-Late Cretaceous residual kaolin deposits, and kaolinitic Cretaceous non-marine and marine sediments in southwestern Minnesota is well documented. Current work in the area from Redwood Falls, Mn. to Fairfax, Mn. is being conducted to understand the detailed regional stratigraphic relationships of the pre-Late Cretaceous residuum and Late Cretaceous sediments that are found on both sides of the Minnesota River valley.

The residual deposits vary greatly in grade, both vertically and horizontally, from kaolinite-rich to grus. The parent rocks for these residual deposits consists of granites and gneisses. A number of factors influence the grade of this residual material. These factors can be grouped into three groups: 1) composition of the parent rock, 2) chemical weathering effects, and 3) physical influences. Presently, some of these residual deposits are used in the production of portland cement, and may soon be used as filler in livestock feed.

Overlying the pre-Late Cretaceous residual deposits is a sequence of secondary kaolinites, composed of kaolinitic sandstones, siltstones, mudstones and lignite. These sediments are discontinuous, commonly filling topographic low areas in the residual deposits. Secondary kaolinites are white to light brown in color, and commonly pisolitic. Near the top of some sections of secondary kaolinites, a pisolite bench of iron-cemented material is present. In the Minnesota River valley, the secondary kaolinites appear to occur in Late Cretaceous stream channel and overbank deposits. The secondary kaolinitic material is presently being mined for use in the manufacture of face-brick.

Late Cretaceous sediments overlie residual and secondary deposits, and are composed of non-marine and marine shales, lignites, sandstones and siltstones. Some of the shale units in this sequence are considered to be ball clays, and are the most economically significant. The ball clays, which are dominantly kaolinite in composition contain organic material, which impart a light gray to black color to the sediments. This package of Late Cretaceous sediments is wide-spread in southwestern Minnesota. Currently, the ball clays are used in face-brick manufacture in Minnesota.

Pleistocene glaciation has subsequently scoured and eroded parts or all of the Late Cretaceous sequence, resulting in deposition of a thick blanket of till and outwash material of varying thickness. Glacial deposits cover much of the study area, leaving the best exposures for study along the walls of the Minnesota River valley and tributaries.

Initial observations concerning the stratigraphic model for the Minnesota River valley between North Redwood and Fairfax include:

1. The grade of the primary kaolinite is dependent upon the type parent material.
2. The degree of weathering of the bedrock to a primary kaolinite is inconsistent. This inconsistency is either the result of differential removal by glacial activity or reflects the Late Cretaceous topography of the area.
3. The secondary kaolinite is discontinuous and variable in thickness across the study area.
4. There is a change in grain size and texture of the secondary kaolinite from east to west.
5. Evidence of fluvial deposition includes the quartz, kaolinitic-supported conglomerate found at the base of the secondary kaolinite.
6. Elevations of the pisolite bench are consistent along Crow Creek and can be used as a time line if the thick pisolitic bench is indeed the result of the same laterization event.
7. The Late Cretaceous non-marine and marine shales are rarely preserved.
8. Sedimentary structures and fossils that would provide a stratigraphic marker are lacking.
9. Organic remains are found in the form of carbonized imprints in the shale, which form the lignitic material. These imprints are the remains of leaves and thin twigs. Tree branches and trunks formed the nucleus for siliceous concretions with the woody material since removed.

These observations are being incorporated into a stratigraphic model for the Late Cretaceous sequence in the Minnesota River valley area.

CHEMISTRY AND METAMORPHISM OF AN ARCHEAN PILLOW BASALT

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Abstract

In southeastern Manitoba, on the western edge of the Superior Province of Archean age, the Bird River greenstone belt is a small sub-province of supracrustal rocks. Pillow basalts are a lower stratigraphic formation, approx. 2 km thick, in a sequence of bimodal mafic and felsic volcanics and clastic meta-sedimentary rocks.

Two samples of basalt have been analysed (both core and rim), plus a sheared basalt, plus a cross-cutting dyke. The compositions of the pillow cores, and the sheared basalt, are similar to other Archean tholeiites of diverse volcanic formations, and to modern pillow tholeiites. They have flat REE patterns, and in Nb-Zr-Y they plot as E-MORB. They are enriched in CO₂ and Sr compared to rims.

The rims of the pillows are darker (abundance of hornblende) and contain common garnet porphyroblasts. They are enriched in Fe³⁺, Fe, Mg, Ca, Mn compared to cores. They also have flat REE patterns, but in Nb-Zr-Y and Ti-Zr-Y they plot outside the field of igneous rocks due to enrichment in Y.

The cross-cutting dyke is an andesite which has not been subject to the alteration seen in the rims of the pillow basalt. Its primary magma is distinct from that of the pillow basalt, as shown by enrichment in light REE, decreasing from La to Dy.

The formations are steeply dipping, and show post-folding shear zones. The alteration of pillow rims is premetamorphic, and did not affect the sheared basalt or the late dyke. During metamorphism, hornblende and cummingtonite have overgrown the S₂ foliation (main folding event). This is interpreted as indicating that heat flow, probably from the adjacent batholithic intrusion, continued after deformation.

Geochemistry of Archean Rocks from the Virginia Horn area: Preliminary Interpretations

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Archean supracrustal rocks exposed in the anticlinal core of the Virginia Horn structure of the Mesabi Iron Range of northeastern Minnesota comprise a sequence of folded metavolcanic and metasedimentary units, some and perhaps all of which are tectonically stacked, and into which are intruded a series of small gold-bearing felsic porphyry bodies. A major through-going structure, the Pike River fault/shear system cuts this sequence. Chemical analyses for major and minor elements have been obtained for a suite of 66 samples representing all principal lithologies.

Metavolcanic rocks of the area are principally flows, some pillowed, with subordinate intercalated fragmental units. Major element analyses of these rocks show them to range in composition from basalt to dacite, with basalt and andesite predominating. The major and minor element data suggest that these rocks are grouped into two distinct geochemical suites. The basaltic rocks show tholeiitic affinities and have flat REE patterns; the andesitic and dacitic rocks have calc-alkaline affinities and are somewhat enriched in the light REE. Rocks in the Gilbert and McKinley areas appear to be tholeiitic, while those in the Biwabik area are calc-alkaline. The nature of the field expression of the transition between these two suites is not yet clear, though the Pike River Fault may play a role.

The felsic porphyries plot in a very tight cluster around 70% SiO₂ and 8% Na₂O + K₂O. These rocks would appear to be more silicic than other dacite porphyries from the Vermilion District. These rocks have undergone sericite-carbonate alteration and the high SiO₂ values might suggest secondary silicification. With the exception of occasional quartz veins, however, there appears to be little petrographic evidence for secondary silicification. Likewise, the consistent SiO₂ values of the various samples would seem to rule out silica introduction. Perhaps the higher SiO₂ values, as occur in these intrusives, might be a clue as to why these bodies are auriferous, while similar-appearing dacitic bodies with lower SiO₂ contents elsewhere in the Vermilion District are not.

Greywackes range from 55-70% SiO₂, the majority plotting as "dacites", suggesting possible derivation from the calc-alkaline portions of the volcanic pile. The composition of these greywackes is consistent with greywackes throughout the Vermilion District.

ARCHEAN AND PROTEROZOIC TECTONO-MAGMATIC ACTIVITY ALONG THE SOUTHERN MARGIN OF THE SUPERIOR PROVINCE IN NORTHWESTERN IOWA, USA

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A Precambrian igneous complex of layered ultramafic and mafic rocks occurs within the basement of northwestern Iowa beneath approximately 300 meters of Phanerozoic sediments. This layered series has been named the Otter Creek complex. It is marked by a circular magnetic anomaly, one of several that lie north and west of an inferred suture that has been postulated as the boundary between the Archean Superior Province and an Early Proterozoic terrane. The layered series is tilted steeply to the northwest; rocks representing the upper portion of the original magma chamber have been removed by erosion or tectonic processes. A block of banded iron formation, itself intruded by lamprophyre dikes, is contained within the layered sequence. The iron formation/lamprophyre block has undergone high-temperature metamorphism followed by a retrograde event.

The banded iron formation was deposited in a supracrustal environment, then intruded by the lamprophyre. This assemblage was apparently incorporated into a mafic magma that subsequently crystallized to form the layered complex. Radiometric dating of the layered rocks and the lamprophyre, using Nd/Sm isotopes, yields an isochron of approximately 2.9 Ga and an ϵ_{Nd} value of zero to slightly negative values. The lamprophyre and layered complex fall on the same isochron and thus appear to be essentially coeval. Archean lamprophyre has been reported from the Superior Province as having been formed during the closing stages of the various subprovinces. Trace element abundances in both the lamprophyre and layered complex are consistent with derivation from a primitive to partially depleted mantle and thus support the isotopic evidence.

The entire layered complex has undergone low-temperature alteration, similar to that seen in other mafic rocks from Archean greenstone belts. We interpret the high-temperature metamorphism experienced by the iron formation and lamprophyre to have occurred during incorporation into the mafic magma and the retrograde metamorphism of these lithologies as resulting from the same event that produced prograde paragenesis of low-temperature minerals in the layered complex. Although most primary phases were replaced with secondary phases such as serpentine, chlorite, uraltic amphibole, epidote, and albite, major chemical redistribution does not appear to have affected these rocks.

A younger Archean quartz monzodiorite gneiss occurs near the layered complex, but the contact relations are not known. The magma from which the monzodiorite originally crystallized

formed at approximately 2523 Ma (Van Schmus et al., 1987). A mantle separation age of 2.9 Ga has been determined for this rock, indicating that it could have formed by partial melting of material derived from the same mantle rocks that produced the Otter Creek layered complex. Tectonic uplift tilted the layered igneous body and the quartz monzodiorite and exposed them to erosion.

Felsic volcanism occurred at approximately 1775 Ma (Wallin and Van Schmus, 1988) and covered the exposed rocks. These volcanics yield a depleted mantle separation age of 2.7 Ga. They are similar in age and stratigraphic position to rhyolites found in central Wisconsin (Smith, 1978; Van Schmus, 1978), but have been more strongly altered than the Wisconsin rhyolites, being depleted in LILE which resulted in a composition equivalent to keratophyre. These volcanics may have formed in the waning stages of the 1850-1900 Ma Penokean Orogeny or they may be related to the proposed 1750 Ma Central Plains Orogeny (Bickford et al., 1986).

Analysis of the combined data indicates the presence of primitive to slightly depleted mantle material to the southern margin of the Superior Craton at approximately 2.9 Ga. Varying degrees of partial melting of this mantle produced lamprophyric dikes and contemporaneous mafic magma bodies, including one which crystallized to form the Otter Creek layered complex. The entire complex subsequently underwent low-temperature alteration, resulting mainly in the formation of hydrous minerals. Subsequent tectono-magmatic activity involving partial melting of rocks derived from the 2.9 Ga mantle source occurred in this region at approximately 2.5 Ga and 1.75 Ga resulting in a quartz monzodiorite plutonic rock and felsic volcanics, respectively.

REFERENCES

- Bickford, M. E., Van Schmus, W. R., and Zeitz, 1986. Proterozoic history of the midcontinent region of North America. *Geology*, 14:492-496.
- Smith, E. I. 1978. Precambrian rhyolites and granites in south-central Wisconsin: Field relations and geochemistry. *Geological Society of America bulletin*, 89:875-890.
- Van Schmus, W. R. 1978. Geochronology of the southern Wisconsin rhyolites and granites. *Geosciences Wisconsin*, 2:19-24.
- Van Schmus, W. R., Bickford, M. E., and Zeitz, I. 1987. Early and middle Proterozoic provinces in the central United States. *In International Lithosphere Program. Edited by A. Kröner. American Geophysical Union Geodynamics Series*, 17:43-68.
- Wallin, E. T., and Van Schmus, W. R. 1988. Geochronological studies of the Archean-Proterozoic transition, north-central United States. *Geological Society of America Abstracts with Programs*, 20:131.

STRUCTURAL ANALYSIS OF THE MIDCONTINENT RIFT BASED ON SLICKENSIDE ANALYSIS

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ABSTRACT

The Midcontinent Rift is a 1.1 billion year feature which has been defined primarily by geophysical studies. Many studies have examined the rift from a petrologic view but few have examined the structural geology in any detail. This study examines the structural aspects of the rift, elucidates the directions of opening and closing, and constrains the timing of the system, by utilizing paleostress stratigraphy. Preliminary field work in Minnesota, Canada, and the Upper Peninsula of Michigan has yielded data on fault and joint populations, from which stress tensors were calculated. Classification of faults and establishment of the sense of movement was accomplished by analyzing slickensides, recrystallization on the fault plane, and Reidel fractures as primary movement indicators. Faults with opposite sense of movement (dextral vs. sinistral, normal vs. reverse) have similar attitudes indicating a 180° reversal of stress direction. This study proposes the direction of opening and closing of the rift was constrained by the geometry of the fault systems and by similar directions of the far field stresses.

A STUDY OF THEMATIC MAPPER LINEAMENTS IN NORTHWEST NEVADA

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Analysts of the 1970's were able to identify major linear patterns (>250km long) such as the Midas Trench and Rye Patch lineaments in the area between Reno and Winnemucca on single-band Landsat-1 images and relate them to the geomorphology and structure of the Basin and Range province. Multiband Thematic Mapper (TM) data with an improved (30m) resolution provide an opportunity to re-examine the area in terms of the spatial distribution of its numerous shorter linear features. 68,000 lineament segments were initially interpreted (primarily from the deeply incised and shadowed ranges) on a 1:100,000 scale band-234 TM image. Subsequent reprocessing of the data with an intensity-hue-saturation (IHS) transformation and edge-enhancement enabled another 36,000 lineament segments to be interpreted from the topographically subdued intervening basins. Digitization of the x-y coordinates of the lineament endpoints was accomplished at a digitizing tablet, using a puck with a head-tail audio prompt and a domain-clearing technique to accommodate lineament clusters.

Once digitized, the TM lineament set became amenable to visualization, manipulation, and analysis as well as coregistration and integration with other spatially addressable data sets such as aeromagnetics, known mining activity, and Digital Elevation Model (DEM) data -- via processing with a geographic information system (GIS). The results of such treatments with the PANACEA GIS have been the focus of presentations by Murdock, Pride, Woodzick and others at meetings in both Canada and the United States. Selected examples from this body of work (e.g., lineament intersection enhancement and comparison of TM/DEM lineament sets) will be discussed with respect to their significance for mineral exploration and in light of the advanced capabilities offered by the next generation of orbital monitoring systems such as RADARSAT and Eos.

GEOSTATISTICAL AND GIS EVALUATION OF BIOGEOCHEMICAL AND ECOLOGICAL DATA FROM
THREE MINERALIZED SITES (Au & Cu-Ni-PGE), NORTHEASTERN MINNESOTA:
IMPLICATIONS FOR MINERAL EXPLORATION IN A BOREAL FOREST

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Detailed biogeochemical and ecological studies of vegetation were conducted in the boreal forest of northeastern Minnesota. These studies were implemented over three mineralized sites:

- 1) Raspberry Prospect: Archean (2.7 Ga) gold mineralization in the Shagawa Shear Zone (SSZ), Vermilion greenstone belt, 5 miles west of Ely, Minnesota;
- 2) Spruce Road (SR): basal Cu-Ni mineralization of the Duluth Complex;
- 3) South Filson Creek (SFC): "cloud zone" Cu-Ni-PGE mineralization of the Duluth Complex.

The two Keweenawan age (1.1 Ga) Duluth Complex sites are 15 miles southeast of Ely. The SR site consists of low grade Cu-Ni sulfide mineralization at the basal contact of the Duluth Complex, whereas the SFC site has discrete, fracture-controlled secondary Cu-Ni-PGM "cloud zone" mineralization. Glacial overburden thickness at the three sites varies from 0-40 ft.

Over 1300 vegetation samples were collected from 17 plant species during 1989 and 1990 at the three sites. Sampling took place over two weeks in late August and early September of both years. Tissue samples (1100) submitted for multi-element INAA and DCP analysis included leaves, twigs, needles, and outer bark.

Analysis of 500 vegetation samples from the Raspberry site in 1989 shows *Abies balsamea* (balsam fir) twigs, *Populus tremuloides* (quaking aspen) leaves, *Corylus cornuta* (beaked hazel) leaves and twigs, *Acer spicatum* (mountain maple) twigs, and *Aster macrophyllus* (large-leaved aster) leaves contain anomalous gold values. Many of the gold anomalies in vegetation overlie a zone of sericite-iron carbonate alteration associated with the SSZ. *A. balsamea* twigs recollected in 1990 verify the gold anomaly.

At the two Cu-Ni sites, 600 tissue samples from *A. balsamea* (twigs), *Picea mariana* (black spruce - twigs and bark), *Pinus banksiana* (jack pine - bark), *Ledum groenlandicum* (labrador tea - twigs), *Chamaedaphne calyculata* (leatherleaf - twigs), *Alnus crispa* (green alder - twigs and leaves), *Alnus rugosa* (speckled alder - twigs and leaves), and *A. macrophyllus* (leaves) were analyzed for base and precious metals. Anomalous levels of Ni, Co, Au, and Pd were found in *A. balsamea* (twigs), *P. mariana* (twigs), *L. groenlandicum* (twigs), and *A. macrophyllus* (leaves). These anomalies appear to correspond closely to the bedrock mineralization.

Bacillus cereus spore counts and other measures of microbial activity in soils were used as bioindicators of natural metal enrichments. *B. cereus* counts, total carbon and nitrogen, nitrogen mineralization, and pH analyses were done on the A horizon of soils collected at 200 ft. intervals across each site. *B. cereus* counts ranged from 1,000 to 576,000 spores/gm soil,

matching spatial variation of soil metal anomalies. Initial results indicate that *B. cereus* counts can be an effective indicator of concealed ore bodies in northern Minnesota. The effectiveness of other soil properties as biogeochemical prospecting tools is being evaluated.

Ecological characterization consisted of identification and quantification of tree, shrub, and herbal species present within 550 tree and herb plots and 1100 shrub plots. Geostatistical interpretation of the tree, shrub, and herb data will be used to map the various plant communities at each site as well as the spatial distribution of metals. A geographical information system (GIS) will be used to determine what spatial relationships exist between the geochemical, geological, ecological, and geographical data. The ecological, nutrient uptake, geostatistical, and GIS studies are being used to better characterize and identify variables that affect metal uptake and concentration by boreal forest vegetation over metallic mineralization.