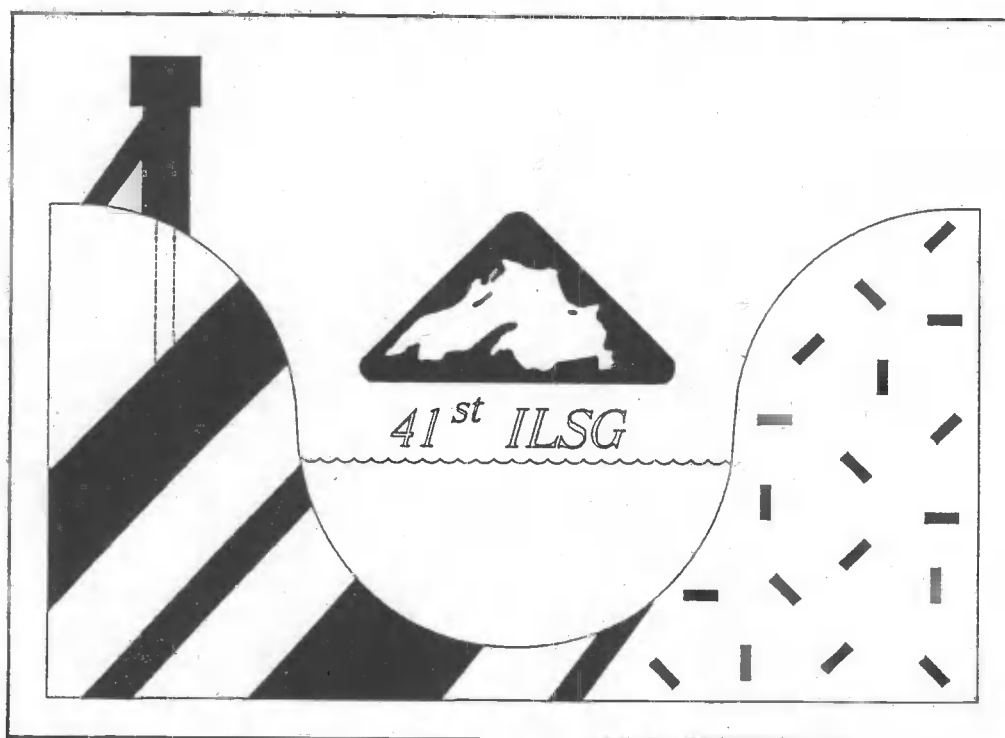


FORTY-FIRST ANNUAL MEETING
INSTITUTE ON LAKE SUPERIOR
GEOLOGY

Marathon, Ontario

May 13-18, 1995



PROCEEDINGS VOLUME 41

PART 1: PROGRAM AND ABSTRACTS

**41st Annual Meeting
Institute on Lake Superior Geology**

Marathon, Ontario May 13-18, 1995

Organizing Committee

General Chairman: Mark Smyk (Ontario Geological Survey)

Secretary-Treasurer: Mark O'Brien (Ontario Geological Survey)

Program Chair / Abstracts Editor: Manfred Kehlenbeck (Lakehead University)

Additional assistance provided by:

Bernie Schnieders, Doug McKay and Maurice Lavigne (Ontario Geological Survey)
with the cooperation of the
Ontario Geological Survey and the Ministry of Northern Development and Mines

Proceedings Volume 41:

Part 1: Abstracts

Part 2: Field Trip Guidebooks

- 2a. Alkalic Rocks of the Midcontinent Rift
- 2b. Geology and Base Metal Deposits of the Manitouwadge Greenstone Belt
- 2c. Geology of the Schreiber Greenstone Assemblage
and its Gold and Base Metal Mineralization
- 2d. Geology and Gold Deposits of the Hemlo Area
- 2e. Kimberlite, Base Metal and Gold Exploration Using Overburden, Wawa Area

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Institute on Lake Superior Geology

**Marathon, Ontario
May 13-18, 1995**

Proceedings Volume 41

Part 1: Program and Abstracts

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Reference to material in Volume 41, Part 1, should follow the example below:

Lightfoot, P.C. The relationship between mantle plumes, flood basalts and mineralization [abst]; Institute on Lake Superior Geology, 41st Annual Meeting, Marathon, ON, 1995, v.41, part 1, p.42-43.

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INSTITUTE ON LAKE SUPERIOR GEOLOGY

<u>INSTITUTE NUMBER</u>	<u>DATE</u>	<u>PLACE</u>	<u>CHAIRMAN</u>
1	1955	Minneapolis, Minnesota	C.E. Dutton
2	1956	Houghton, Michigan	A.K. Snelgrove
3	1957	East Lansing, Michigan	B.T. Sandefur
4	1958	Duluth, Minnesota	R.W. Marsden
5	1959	Minneapolis, Minnesota	E.N. Cameron & R.A. Hoppin
6	1960	Madison, Wisconsin	E.N. Cameron
7	1961	Port Arthur, Ontario	E.G. Pye
8	1962	Houghton, Michigan	A.K. Snelgrove
9	1963	Duluth, Minnesota	H. Lepp
10	1964	Ishpeming, Michigan	A.T. Broderick
11	1965	St. Paul, Minnesota	P.K. Sims & R.K. Hogberg
12	1966	Sault Ste. Marie, Michigan	R.W. White
13	1967	East Lansing, Michigan	W.J. Hinze
14	1968	Superior, Wisconsin	A.B. Dickas
15	1969	Oshkosh, Wisconsin	G.L. LaBerge
16	1970	Thunder Bay, Ontario	M.W. Bartley & E. Mercy
17	1971	Duluth, Minnesota	D.M. Davidson
18	1972	Houghton, Michigan	J. Kalliokoski
19	1973	Madison, Wisconsin	M.E. Ostrom
20	1974	Sault Ste. Marie, Ontario	P.E. Giblin
21	1975	Marquette, Michigan	J.D. Hughes
22	1976	St. Paul, Minnesota	M. Walton
23	1977	Thunder Bay, Ontario	M.M. Kehlenbeck
24	1978	Milwaukee, Wisconsin	G. Mursky
25	1979	Duluth, Minnesota	D.M. Davidson
26	1980	Eau Claire, Wisconsin	P.E. Meyers
27	1981	East Lansing, Michigan	W.C. Cambray
28	1982	International Falls, Minnesota	D.L. Southwick
29	1983	Houghton, Michigan	T.J. Bornhorst
30	1984	Wausau, Wisconsin	G.L. LaBerge
31	1985	Kenora, Ontario	C.E. Blackburn
32	1986	Wisconsin Rapids, Wisconsin	J.K. Greenberg
33	1987	Wawa, Ontario	E.D. Frey & R.P. Sage
34	1988	Marquette, Michigan	J. S. Klasner
35	1989	Duluth, Minnesota	J.C. Green
36	1990	Thunder Bay, Ontario	M.M. Kehlenbeck
37	1991	Eau Claire, Wisconsin	P.E. Meyers
38	1992	Hurley, Wisconsin	A.B. Dickas
39	1993	Eveleth, Minnesota	D.L. Southwick
40	1994	Houghton, Michigan	T.J. Bornhorst
41	1995	Marathon, Ontario	M.C. Smyk

CONSTITUTION OF THE 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 insure 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 was 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 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
G.B. Morey
Greg Mursky

GOLDICH MEDAL COMMITTEE 1994-95

Glen Adams (1995)

Crystal Exploration, Inc., Crystal Falls, MI 44420

Penelope. Morton (1996)

Department of Geology, University of Minnesota Duluth, Duluth, MN

Ken Card (1997)

Geological Survey of Canada, Ottawa, ON K1A 0E8

GOLDICH MEDALISTS

1979 Samuel S. Goldich
1980 *not awarded*
1981 Carl E. Dutton, Jr.
1982 Ralph W. Marsden
1983 Burton Boyum
1984 Richard W. Ojakangas
1985 Paul K. Sims
1986 G.B. Morey

1987 Henry H. Halls
1988 Walter S. White
1989 Jorma Kalliokoski
1990 Kenneth C. Card
1991 William J. Hinze
1992 William F. Cannon
1993 Donald W. Davis
1994 Cedric Iverson

1995 Gene LaBerge

1995 Goldich Medal Recipient
Gene LaBerge

Citation

Gene L. LaBerge, 1995 Goldich Medal Recipient

For all of you associated with the Institute on Lake Superior Geology, I am pleased and honored to introduce you to Gene L. LaBerge as this year's recipient of the Sam Goldich Medal. The medal is awarded "to a geologist whose name is associated with a substantial interest in, or a major contribution to, the geology of the Lake Superior region". Gene is certainly worthy on both counts.

Gene was born and raised in Ladysmith, Wisconsin, appropriately, the home of the recently developed Flambeau mine.

After a stint in the U.S. Marine Corps, he began his geology education at UW-Superior, eventually obtaining his B.S., M.S. and Ph.D. degrees in geology from UW-Madison. The topic of his dissertation related to the origin of magnetite in iron-formation.

Gene's first two summer jobs, while he was a graduate student, introduced him to aspects of geology that were to become his primary research interests. In 1957, he was hired by Ralph Marsden of U.S. Steel in Ishpeming, Michigan to explore for iron-formation. Ralph and Stan Tyler of UW-Madison, Gene's future Ph.D. advisors, would include the summer help on regional field trips to look at iron-formation. Gene claims that it was a direct result of the questions posed by Ralph and Stan that inspired his research interest in this area. It has led to 6 publications in international journals, numerous presentations at national meetings, and the editing of a book on Precambrian iron-formations. In 1958, Gene worked for U.S. Steel as a field assistant to Ced Iverson doing a pebble survey in Wisconsin. After identifying several billion pebbles that summer, Gene was convinced that the Precambrian geology of Wisconsin was more than a "green blob" on the map. In 1969, he conceived and initiated a regional mapping and Natural History Survey under the direction of George F. Hanson. On the advice of Carl Dutton, the project was begun in central Wisconsin near Wausau. Since 1982, support for this on-going research has been provided by the U.S. Geological Society. This program has resulted in several national publications, numerous reports and maps for both the WGNHS and the USGS, and over 30 papers at professional meetings. In 1994, this work was collated to form the basis of his book, Geology of the Lake Superior Region.

I know Gene best in the role of educator. In 1965, he joined the faculty at UW-Oshkosh as the third member of the department with the charge of designing and building the geology program. Since he began teaching, he has led in excess of 100 overnight student trips. I remember Gene saying that he "walked over more of Wisconsin than almost anyone -- from Baraboo to Lake Superior". We didn't doubt it, but wondered if he meant to add "on the same trip". He sure seemed to have the stamina. Recently Gene confided in me that a major stimulus for his work in central Wisconsin was the students' questions, "So simple, yet so difficult to answer". As a testament to his success in academia, Gene has received all of the teaching and research awards that UW-Oshkosh offers, the only faculty member to have done so.

Gene also has a long history with the ILSG. Gene attended his first meeting in Duluth in 1958 and presented his first paper at the 1960 meeting in Madison. Since that time, he has presented over 20 papers and led or co-led 5 field trips with accompanying guides.

Through the years, Gene and I have interacted on many levels, teacher, mentor, fellow guitar player, researcher, colleague and most rewardingly, as a friend. As the 16th recipient of the Goldich Medal, he joins an elite and distinguished group. I am pleased to present to you, Gene LaBerge.

Tim Flood
Natural Sciences Division, St. Norbert College
DePere, Wisconsin

BANQUET SPEAKER

Peter Lightfoot (Ontario Geological Survey, Sudbury)
The relationship between mantle plumes, flood basalts and mineralization

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.

INSTITUTE ON LAKE SUPERIOR GEOLOGY	
<i>Student Travel Award Application</i>	
Please print:	
Student Name: _____	Date: _____
Address: _____	
I certify that the above named person is an active resident student.	

Department Head - Typed	

Department Head - Signature	Date
Educational Status: _____	
Are you the Senior Author of an oral or poster paper? Yes _____ No _____	
Will any other students will be traveling with you? _____ How many? _____	
Statement of Need: (If you need more room, please use the back of the page.)	
Other Significant Details:	

Please return to:	

BOARD OF DIRECTORS

1995 Mark C. Smyk, Chairman
Ontario Geological Survey, Thunder Bay, Ontario P7E 6E3

1994 Theodore J. Bornhorst
Michigan Technological University, Houghton, Michigan 49931

1993 David L. Southwick
Minnesota Geological Survey, St. Paul, Minnesota 55114

1992 Albert B. Dickas
University of Wisconsin-Superior, Superior, Wisconsin 54880

Secretary-Treasurer
Mark Jirsa
Minnesota Geological Survey
2642 University Ave.
St. Paul, MN 55114-1057

LOCAL COMMITTEES

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Ontario Geological Survey, Field Services Section
Thunder Bay, ON P7E 6E3

PROGRAM CHAIR AND ABSTRACTS EDITOR

Manfred Kehlenbeck
Department of Geology, Lakehead University
Thunder Bay, ON P7B 5E1

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Mark O'Brien
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Thunder Bay, ON P7E 6E3

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Bernie Schnieders, Doug McKay and Maurice Lavigne
Ontario Geological Survey, Field Services Section
Thunder Bay, ON P7E 6E3

STUDENT PAPER COMMITTEE

Mark Jirsa (Chair)

Minnesota Geological Survey
St. Paul, MN 55114-1057

Virginia Peterson

Department of Geosciences and Anthropology, Western Carolina University
Cullowhee, NC 28723-9047

David Laderoute

Ontario Geological Survey, Field Services Section
Thunder Bay, ON P7E 6E3

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Ted Bornhorst

Michigan Technological University
Houghton, MI 49931

Mark Jirsa

Minnesota Geological Survey
St. Paul, MN 55114-1057

Maurice Lavigne

Ontario Geological Survey, Field Services Section
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Jim Miller

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United States Geological Survey
St. Paul, MN 55112

Eva Zaleski

Geological Survey of Canada
Calgary, AB T2L 2A7

REPORT OF THE CHAIRMAN 40TH ANNUAL INSTITUTE ON LAKE SUPERIOR GEOLOGY HOUGHTON, MICHIGAN

The 40th Annual Institute on Lake Superior Geology was held May 11-14, 1994 on the campus of Michigan Technological University in Houghton, Michigan. The meeting was hosted by the Department of Geological Engineering, Geology, and Geophysics with assistance from the Division of Education and Public Services. The meeting Chairman was Theodore J. Bornhorst who handled all aspects of the meeting including the technical sessions and the field trips.

The Proceedings of the 40th Annual ILSG was published in 5 parts as Volume 40, Part 1: Program and Abstracts edited by Theodore J. Bornhorst and S. Douglas McDowell, and a series of 4 field trips, including; Part 2: Self-guided geological field trip to the Keweenaw Peninsula, Michigan by Theodore J. Bornhorst and William I. Rose; Part 3: Volcanic geology of eastern Isle Royale, Michigan by William I. Rose; Part 4: Michigan kimberlites and diamond exploration techniques by Shawn M. Carlson and Wayne Floodstrand; and Part 5: Lessons from mining case histories: West Menominee Range, Michigan by Allan M. Johnson. For the field trip to the White Pine and Caledonia Mines no ILSG guidebook was published and instead the trip used Society of Economic Geologists Guidebook Series Volume 13 titled "Keweenawan Copper Deposits of Western Upper Michigan" edited by Theodore J. Bornhorst. Field trips continue to be an important component of the ILSG. The field trip to Isle Royale National Park was the first ever geological field trip to the island.

A total of 154 people registered for the meeting. Field trips attracted 121 paid participants, including: 24 for Keweenaw Peninsula, 13 for Isle Royale, 41 for Michigan kimberlites, 13 for Menominee Range and 30 for White Pine/Caledonia.

The annual banquet was attended by about 105 people. Cedric Iverson was awarded the Institute's prestigious Goldich Medal. The banquet address was given by Geoffrey S. Plumlee, U. S. Geological Survey. His topic was "The crucial (but underutilized) role of the economic geologist in predicting and remediating the environmental effect of mineral resource development."

Optional lunch was offered on both days of the technical sessions and featured speakers, Larry Lankton on Keweenaw Peninsula mining history and Stan Dyl on minerals in Russia. The lunch program was well received as a total of 140 attended the two lunches.

The best student paper awards went to Nicholas Van Wyck, University of Wisconsin, Madison and Elizabeth Kropf, Macalester College for best oral or poster presentation, respectively. Student travel awards, for a total of \$375, were awarded to Elizabeth Kropf, Leslie Magnus, Gwendolyn Miner, Micheal Rogers, and Mark Schmitz.

In 1993, the Board of Directors had a lengthy discussion on the future of the ILSG. At this time they directed the incoming Chairman, T.J. Bornhorst, to increase the "environmental" component of the 40th Annual meeting. In response to this directive, "environmental" papers were solicited which resulted in 20% of the abstracts being "environmental" as compared to a median of 2% in this topic category for past meetings (by far the 40 year high). A mining-related environmental field trip was solicited (Menominee Range) and the banquet speaker addressed a mining-related environmental topic. These changes in topics covered by the ILSG seemed to be well received by the meeting participants.

The Board of Directors of the Institute on Lake Superior Geology met in Houghton, Michigan on May 12, 1994. In attendance were T.J. Bornhorst (Chairman), A.B. Dickas, G.L. LaBerge for Paul Meyers, Jim Miller for Dave Southwick, and M.G. Mudrey, Jr. (Secretary-Treasurer). Guests included Mark Smyk, Bill Cannon, and R. Sage. Actions taken were:

1. Approved an offer by the Ontario Geological Survey to host the 41st Annual Institute (1995) in Marathon, Ontario. Mark Smyk will be Chairman.

2. Approved an offer by the U. S. Geological Survey to host the 42nd Annual Institute (1996) near Cable, Wisconsin. Laurel Woodruff will be the first ever woman Chair of the Institute on Lake Superior Geology.
3. Endorsed an offer by the Ontario Geological Survey to host the 43rd Annual Institute (1997) in Sudbury, Ontario. Approval will be necessary at a future meeting of the Board of Directors.
4. Appointed Theodore J. Bornhorst to the post of Associate Secretary-Treasurer. This action was taken to facilitate selling the popular Keweenaw Peninsula field guidebook under the auspices of the Institute. The Associate Secretary-Treasurer will be backup the signature on the Institute accounts.
5. Received and accepted a Financial Report from Secretary-Treasurer Mudrey. The net assets of the Institute on Lake Superior Geology as of May 10, 1994 are \$9,965.26. Student travel and paper awards and 39th Annual meeting overrun accounted for \$3411.27 net decrease in assets. To help avoid future decrease in assets the Board of Directors agreed that Student Travel Awards be limited to interest on investments (the Chairman should contact the Secretary-Treasurer to determine the amount to be awarded) and that Student Paper Awards should be funded by the local meeting budget.
6. Approved Cedric Iverson for the 1994 Goldich Medal Award.
7. Appointed K. Card (representing government) to a 3 year term on the Goldich Medal Committee.
8. Discussed ownership of Institute field trip guidebooks and agreed that the Institute owned the guidebooks only when it paid for printing.
9. Discussed the future of the Institute. Agreed that environmental topics need not be solicited for the Marathon meeting (41st ILSG) next year, but for the Cable, Wisconsin (42nd ILSG) it may be desirable to once again solicit environmental material for the ILSG.
10. Approved an election for the position of Secretary-Treasurer for a term of two years. The Board discussed the need to have elections on a more regular schedule. It was agreed that elections should be held, at least, every 4 years.

The election for a new Secretary-Treasurer was held on May 12, 1994 at the annual banquet. Mark Jirsa, Minnesota Geological Survey, was elected to the post. I am sure the institute's finances are in good hands.

Financially the 40th Annual ILSG was an overwhelming success. The combination of excellent budget help of Marty Banks and Mary Rouleau, Michigan Tech Division of Education and Public Services and advice from Dave Southwick helped me avoid the deficit which occurred from the meeting last year. I am pleased to report a profit of about \$4,000 from the 40th Annual meeting. Exact numbers are not possible since publications continue to be sold. The Keweenaw Peninsula guidebook (Volume 40, Part 2), published and distributed by the Institute on Lake Superior Geology, is now in its second printing as the first printing of 250 copies is sold out. Profits from sale of the guidebook will go the Institute's treasury.

On a personal note, I'm glad to be finished with the task of being Chairman of the 40th Institute on Lake Superior Geology. It is easier being Chairman the second time, but it still requires a lot of work. I thank all those who have given me positive feedback, since this helps make all of the work more worth doing. Despite the disappointment for the White Pine/Caledonia field trip when a totally unexpected mine fire precluded going underground at White Pine, I consider the 40th ILSG to have been a very successful meeting.

Respectively Submitted,

Theodore J. Bornhorst
Chairman 40th ILSG
September 19, 1994
Houghton, Michigan

PROGRAM

CALENDAR OF EVENTS AND PROGRAM

PRE-MEETING FIELD TRIPS

Field trips depart from the Marathon Recreation Complex at 8:00 a.m. and return each evening by about 6:00 p.m.

SATURDAY MAY 13, 1995

FIELD TRIP 1a **(DAY ONE OF TWO DAYS)**
ALKALIC ROCKS OF THE MIDCONTINENT RIFT

FIELD TRIP 2A **(DAY ONE OF TWO DAYS)**
MANITOUWADGE GREENSTONE BELT

SUNDAY MAY 14, 1995

FIELD TRIP 1a **(DAY TWO OF TWO DAYS)**
ALKALIC ROCKS OF THE MIDCONTINENT RIFT

FIELD TRIP 2a **(DAY TWO OF TWO DAYS)**
MANITOUWADGE GREENSTONE BELT

FIELD TRIP 3a
SCHREIBER GREENSTONE ASSEMBLAGE

FIELD TRIP 4
HEMLO GREENSTONE BELT I: REGIONAL GEOLOGY

SUNDAY MAY 14, 1995

MARATHON RECREATION COMPLEX
4:00 pm. - 10:00 pm.

REGISTRATION - **POSTER SESSION** (authors at posters) - **CASH BAR MIXER**

MONDAY MAY 15, 1995

REGISTRATION CONTINUES
8:00 am - 4:30 pm

TECHNICAL PROGRAM

MONDAY MAY 15, 1995

MORNING - SESSION I

CHAIRS: Ted Bornhorst and Eva Zaleski

8:45 **WELCOME**

1. 8:50 BERENDSEN, P. HISTORY AND DEVELOPMENT OF THE SOUTHERN EXTENSION OF THE MID-CONTINENT RIFT IN KANSAS
2. ** HALLS, H.C. ARE THE MAJOR THRUST FAULTS OF THE MID-CONTINENT RIFT
MANSON, M.L. AND THE KAPUSKASING ZONE PART OF THE SAME TECTONIC
ZHANG, B. ZONE?
3. 9:10 CORFU, F. U-Pb GEOCHRONOLOGY OF THE SHEBANDOWAN GREENSTONE
STOTT, G.M. BELT, SUPERIOR PROVINCE ONTARIO
4. 9:30 * KING, D. DEPOSITIONAL SYSTEMS ASSOCIATED WITH THE 3.0 GA
FRALICK, P.W. FINLAYSON AND LUMBY LAKE GREENSTONE BELTS,
NORTHWESTERN ONTARIO

9:50 **COFFEE BREAK AND POSTER SESSION**

5. 10:20 LaBERGE, G.L. NEW OBSERVATIONS ON THE GEOLOGY OF THE WESTERN
CANNON, W.F. GOGEBIC IRON RANGE, NORTHERN WISCONSIN
KLASNER, J.S.
6. 10:40 * PUFAHL, P.K. PALEOGEOGRAPHIC RECONSTRUCTION OF THE GUNFLINT-
FRALICK, P.W. MESABI-CUYUNA DEPOSITIONAL SYSTEM: A BASIN ANALYSIS
APPROACH
7. 11:00 * PETERSON, D.M. TARGETING MASSIVE SULFIDE DEPOSITS EXPLORATION IN THE
WESTERN VERMILLION DISTRICT: VOLCANOLOGICAL CONTROLS
8. 11:20 * SHORE, G. ON THE ORIGIN OF ALKALINE GABBROIC ROCKS IN THE
COLDWELL PENINSULA AREA, COLDWELL ALKALINE COMPLEX,
ONTARIO
9. 11:40 JIRSA, M.A. EXTENSION OF THE WISCONSIN MAGMATIC TERRANES INTO
CHANDLER, V.M. THE MINNESOTA SEGMENT OF THE PENOKEAN OROGEN
BOERBOOM, T.J.

NOON **LUNCH BREAK**

* Student paper

** cancelled paper

MONDAY MAY 15, 1995

AFTERNOON - SESSION II

CHAIRS: Jim Miller and Maurice Lavigne

- | | | | |
|-----|------|-------------------------------|---|
| 10. | 2:00 | * SCHNEIDER, D.A.
HOLM, M. | COMPARISON OF POST-PENOKEAN THERMAL HISTORIES OF THE WATERSMEET AND REPUBLIC DISTRICTS, NORTHERN MICHIGAN: RESULTS AND IMPLICATIONS OF 40 Ar/39 Ar MINERAL AGE DATING |
| 11. | 2:20 | HOLM, D.K. | THERMOCHRONOLOGY OF CENTRAL MINNESOTA REVISITED: IMPLICATIONS FOR THE POST-COLLISIONAL EVOLUTION OF THE PENOKEAN OROGENIC BELT |
| 12. | 2:40 | * DARRAH, K.S.
HOLM, D.K. | APPLICATION OF THE ALUMINUM-IN-HORNBLENDE BAROMETER ON EARLY PROTEROZOIC, POST-PENOKEAN PLUTONS, CENTRAL MINNESOTA |

3:00 COFFEE BREAK AND POSTER SESSION

- | | | | |
|-----|------|-------------------------------------|--|
| 13. | 3:30 | * KOEBERNICK, C.F.
FRALICK, P.W. | NEOARCHEAN COASTAL SEDIMENTATION IN THE SHEBANDOWAN GROUP, NORTHWESTERN ONTARIO |
| 14. | 3:50 | NORTH, J. | KEWEENAWAN UPLIFT AND SUPERGENE OXIDATION OF PRE-PENOKEAN, SUPERIOR TYPE IRON FORMATION |
| 15. | 4:10 | * FEHER, L.
FLOOD, T. | VESICLES AND BRECCIA DUE TO INJECTION OF MAFIC MAGMA INTO PARTIALLY LITHIFIED SEDIMENTS OF THE EARLY PROTEROZOIC IRONWOOD IRON FORMATION WESTERN GOGEBIC RANGE, NW WISCONSIN |

4:30 SESSION END

6:00 MOOSE HALL - MIXER - CASH BAR

7:30 MOOSE HALL - BANQUET AND AWARDS PRESENTATION
Banquet Speaker: Peter Lightfoot - The relationship between mantle plumes, flood basalts and mineralization.

*** Student paper**

TUESDAY MAY 16, 1995

MORNING - SESSION III

CHAIRS: Laurel Woodruff and Bernie Schnieders

- | | | | |
|-----|------|--|---|
| 16. | 8:30 | LIN, S.
ŠKULSKI, T.
PERCIVAL, J. | STRUCTURAL GEOLOGY AND TECTONIC EVOLUTION OF THE
VIZIEN GREENSTONE BELT IN MINTO BLOCK, NORTHEASTERN
SUPERIOR PROVINCE, NORTHERN QUEBEC |
| 17. | 8:50 | PETERSON, V.L.
ZALESKI, E.
BREEMEN, O. | STRUCTURAL EVOLUTION AND AGE RELATIONSHIPS OF THE
MANITOUWADGE GREENSTONE BELT AND WAWA-QUETICO
SUBPROVINCE, SOUTHWESTERN SUPERIOR PROVINCE,
ONTARIO |
| 18. | 9:10 | ZALESKI, E. | GEOLOGICAL SETTING AND GEOCHEMISTRY OF MASSIVE
SULFIDE DEPOSITS AND ALTERATION ZONES IN THE
MANITOUWADGE GREENSTONE BELT, NORTHWESTERN
ONTARIO |
| 19. | 9:30 | FRALICK, P.W.
PURDON, R. | NEOARCHEAN TRANSUBPROVINCE DEPOSITIONAL SYSTEMS:
TEMPORAL VS. SPACIAL VARIABILITY IN WESTERN SUPERIOR
PROVINCE |

9:50 COFFEE BREAK AND POSTER SESSION

- | | | | |
|-----|-------|--|---|
| 20. | 10:20 | BORNHORST, T.J.
WHITEMAN, R.C. | NATIVE COPPER AND ASSOCIATED MINERALS IN BASALTS
AT THE CALEDONIA MINE, WESTERN UPPER MICHIGAN |
| 21. | 10:40 | SHAW, C.S.J. | GEOCHEMISTRY AND FRACTIONATION OF THE EASTERN
GABBRO, COLDWELL ALKALINE COMPLEX |
| 22. | 11:00 | LIGHTFOOT, P.C.
FARRELL, K.
MOORE, M.
PEKESKI, D.
CRABTREE, D.
KEYS, R.R. | GEOCHEMICAL VARIATIONS WITHIN THE SUBLAYER AND THE
MAFIC-ULTRAMAFIC INCLUSIONS, WHISTLE MINE, SUDBURY
IGNEOUS COMPLEX, CANADA |
| 23. | 11:20 | LEE, I.
RIPLEY, E.M. | GENESIS OF Cu-Ni SULFIDE MINERALIZATION AT THE
SPRUCE ROAD DEPOSIT, SOUTH KAWISHIWI INTRUSION,
DULUTH COMPLEX |
| 24. | 11:40 | MILLER, J.D., Jr. | PREDICTION AND DISCOVERY OF PGE OCCURRENCES IN THE
DULUTH COMPLEX AT DULUTH |

NOON **LUNCH BREAK**

POSTERS MUST BE REMOVED BY NOON TODAY

TUESDAY MAY 16, 1995

AFTERNOON - SESSION IV

CHAIRS: Mark Jirsa and Cliff Shaw

25. 2:00 ZBIKOWSKI, D.W. A CONTINENTAL CRUST FRACTURE INITIATION PATTERN AND
HYPOTHETICAL MECHANISM

26. 2:20 ZBIKOWSKI, D.W. DERIVATIVE CONTINENTAL INDICATIONS OF A CURVILINEAR
CARIBBEAN MANTLE CONVECTION PLUME

2:40 **PRESENTATION OF STUDENT PAPER AWARDS**

2:50 **COFFEE BREAK AND POSTER SESSION**

27. 3:20 MORRIS, T.F. HEAVY MINERAL INDICATORS, WAWA AREA
MURRAY, C.
CRABTREE, D.

28. 3:40 RUDASHEVSKY, N.S. PRODUCTS OF ELECTRIC PULSE DISAGGREGATION OF SOME
WEIBLEN, P.W. KEWEENAWAN ROCKS
STOYNOV, H.

29. 4:00 FREY, B. CENTRAL MINNESOTA, U.S.A. CORE LOGGING AND ASSAY
DATABASES

7:00 - 10:00 pm.

WINE AND CHEESE

HOSTED: BY Hemlo Branch of the Canadian Institute of Mining and Metallurgy at
the Royal Canadian Legion

4:20 **CLOSING REMARKS**

4:30 **SESSION END**

POSTER PRESENTATIONS

Authors are requested to be present at their posters during scheduled times.

<u>Senior Author</u>	<u>Title</u>
** CARD, K.	LITHO-TECTONIC AND MINERAL DEPOSIT MAPS OF THE SUPERIOR PROVINCE
DESAUTELS, P.	DAVID-BELL MINE
GERE, M.	CURRENT INVENTORY OF MICHIGAN'S GEOLOGICAL CORE AND SAMPLE REPOSITORY AT MARQUETTE
* EVEREST, J.	IGNEOUS CHARACTERISTICS OF THE MATRIX TO THE FOOTWALL BRECCIA, NORTH RANGE, SUDBURY STRUCTURE, CANADA
* DAVIS, D.	GEOCHRONOLOGY OF THE 1.1 GA NORTH AMERICAN MID-CONTINENT RIFT
GREEN, J.	GEOLOGY OF THE NORTH SHORE STATE PARKS
* KÄRKKÄINEN, N.	TITANIUM ORE POTENTIAL OF GABBROS: EXAMPLES FROM WESTERN FINLAND
LAWLER, T.	MINERAL POTENTIAL EVALUATION, CENTRAL MINNESOTA
LIGHTFOOT, P.C.	GEOCHEMICAL RELATIONSHIPS BETWEEN THE SUBLAYER, MAIN MASS, AND OFFSETS, SUDBURY IGNEOUS COMPLEX, CANADA
MORRIS, T.	KIMBERLITE HEAVY MINERAL INDICATORS IN OVERBURDEN, MICHIPICOTEN RIVER-WAWA AREA, NORTHEASTERN ONTARIO
MUIR, T.	THE CURRENT SETTING OF THE HEMLO GOLD DEPOSIT, ONTARIO: IMPORTANCE OF FUNDAMENTAL RELATIONSHIPS
* PETERSON, D.M.	GEOLOGICAL, GEOPHYSICAL AND GEOCHEMICAL COMPILATION OF THE WESTERN VERMILLION DISTRICT: TARGETING FOR GOLD AND MASSIVE SULFIDE DEPOSITS
SAGE, R.	KIMBERLITE IN ONTARIO
SEVERSON, M.	GEOLOGY OF THE SOUTHERN PORTION OF THE DULUTH COMPLEX
SKRECKY, G.	WILLIAMS MINE
VIITALA, R.	EFFECTS OF LARGE METEORITE IMPACTS ON CRUSTAL ROCKS - SUDBURY BASIN IN THIN SECTION
WOLFSON, I.	THE GECO MINE, MANITOUWADGE, ONTARIO: A VOLCANOGENIC MASSIVE SULPHIDE DEPOSIT (see Lockwood, H. for abstract)
WOODRUFF, L.	PROPOSED FIELD TRIPS FOR THE 42ND ANNUAL INSTITUTE ON LAKE SUPERIOR GEOLOGY

* Student Paper

** cancelled paper

POST MEETING FIELD TRIPS

Field trips depart from the Marathon Recreation Complex at 8:00 a.m. All field trips, except trip number 6, return to Marathon each evening by about 6:00 p.m.

WEDNESDAY, MAY 17, 1995

FIELD TRIP 1b (DAY ONE OF TWO DAYS)
ALKALIC ROCKS OF THE MIDCONTINENT RIFT

FIELD TRIP 2b (DAY ONE OF TWO DAYS)
MANITOUWADGE GREENSTONE BELT

FIELD TRIP 3b
SCHREIBER GREENSTONE ASSEMBLAGE

FIELD TRIP 5
HEMLO GREENSTONE BELT II: DEPOSIT GEOLOGY

FIELD TRIP 6 (DAY ONE OF TWO DAYS)
WAWA KIMBERLITE/GOLD EXPLORATION
OVERNIGHT STAY AT WAWA AT PARTICIPANT'S EXPENSE

WEDNESDAY, MAY 17, 1995

FIELD TRIP 1b (DAY TWO OF TWO DAYS)
ALKALIC ROCKS OF THE MIDCONTINENT RIFT

FIELD TRIP 2b (DAY TWO OF TWO DAYS)
MANITOUWADGE GREENSTONE BELT

FIELD TRIP 6 (DAY TWO OF TWO DAYS)
WAWA KIMBERLITE/GOLD EXPLORATION
RETURN TO MARATHON BY ABOUT 6:00 PM.

ORAL PRESENTATIONS

<u>Senior Author</u>	<u>Session No. - Paper No.</u>
BERENDSEN, P.	I - 1
BORNHORST, T.	III - 20
CORFU, P.	I - 3
* DARRAH, K.	II - 12
* FEHER, L.	II - 15
FRALICK, P.	III - 19
FREY, B.	IV - 29
** HALLS, H.	I - 2
HOLM, D.	II - 11
JIRSA, M.	I - 9
* KING, D.	I - 4
* KOEBERNICK, C.	II - 13
LaBERGE, G.	I - 5
LEE, I.	III - 23
LIGHTFOOT, P. (1).	III - 22
LIGHTFOOT, P. (2).	Banquet Presentation
LIN, S.	III - 16
MILLER, J.	II - 24
MORRIS, T.	IV - 27
NORTH, J.	II - 14
* PETERSON, D.M.	I - 7
PETERSON, V.	III - 17
* PUFAHL, P.	I - 6
RUDASHEVSKY, N.S.	IV - 28
* SCHNEIDER, D.	II - 10
SHAW, C.	III - 21
* SHORE, G.	I - 8
ZALESKI, E.	III - 18
ZBIKOWSKI, D. (1).	IV - 25
ZBIKOWSKI, D. (2).	IV - 26

*Student Paper

**cancelled paper

ABSTRACTS

HISTORY AND DEVELOPMENT OF THE SOUTHERN EXTENSION OF THE MIDCONTINENT RIFT IN KANSAS.

BERENDSEN, Pieter, Kansas Geological Survey, University of Kansas, Lawrence, KS 66047.

Igneous and sedimentary rocks associated with the southern extension of the Midcontinent Rift System (MRS) in Kansas terminate against a regionally significant northwest-trending structural zone (Missouri Gravity Low) at the Kansas-Nebraska border. To the south, an equally pronounced structural zone (Fall River Tectonic Zone) defines a boundary south of which no rift-related igneous or sedimentary rocks occur at the basement surface. The southern boundary also roughly coincides with the suture between the older (1.63-1.80 Ga) metamorphic and granitoid rocks of the Central Plains orogen to the north (Sims and Peterman, 1986) and younger (1.35-1.48 Ga) rhyolitic and dacitic volcanic rocks and associated epizonal granitic plutons to the south (Denison, and others, 1984). North-northeast-trending faults identified in the subsurface are not as pronounced north and south of these sutures. NW-SE- and NNE-WSW-trending faults have been reactivated throughout geologic time. The distribution pattern of Precambrian and Paleozoic rocks within the area comprising the trend of the rift has been greatly influenced by motion along these faults. Renewed movement along basement faults resulted in complex sets of closely spaced faults affecting younger rocks, and are referred to as tectonic zones. The Nemaha and Peace Creek tectonic zones are the major NNE-trending rift-related structures. SW-NE-trending tectonic zones are believed to be older (Clendenin, and others, 1989) and cross the rift zone. The Fall River, Chesapeake, Bolivar-Mansfield tectonic zones and the Missouri Gravity Low are the better known structures.

Magmatic activity associated with the active phase of rifting was essentially synchronous along its length. A concordant U-Pb age of 1097.5 ± 3 Ma obtained from baddeleyite in gabbro from a depth of about 900 m. is within the range of published ages (Van Schmus, 1992). In the post-igneous stages of rifting initially coarse and immature sedimentary rocks followed by finer grained and more mature strata were deposited in axial and flanking basins. There is no geologic record indicating that sedimentary or igneous rocks accumulated in the time span between the end of the Keweenawan and the onset of the Paleozoic, but instead the area was subjected to a long period of erosion and peneplanation. Faulting, as evidenced by considerable vertical displacement of Proterozoic igneous and sedimentary rocks (Woelk and Hinze, 1991; Berendsen, in press) played an important role in preserving younger rocks in graben structures and exhuming older rocks on horst blocks.

Rocks of Permian age are the youngest sedimentary strata to be deposited in the area. Closely coinciding with the western edge of the rift province Cretaceous rocks are present. They are believed to have extended farther to the east, but were eroded back to their present position, possibly related to reactivation of rift structures. The occurrence of numerous Cretaceous (90 Ma) kimberlites occurring at or near the surface as well as non-deposition or erosion of several pre-Permian sedimentary rock units indicate that significant tectonic activity took place at various times during the Paleozoic and Mesozoic eras. The stresses responsible for all this activity originated at the eastern margins of the North American craton during continent to continent collisions beginning during Grenville time and shifting to the south with a major period of activity affecting the midcontinent during the Ouachita-Wichita-Marathon orogeny. Since Permian sedimentary rocks are the youngest strata in the area under discussion it is difficult, if not impossible, to document Cenozoic and recent tectonic activity (probably of lesser intensity) that

undoubtedly must occurred. The stresses are believed to have been transmitted primarily via Precambrian basement rocks and mostly along pre-existing fractures. The shift in direction from which the stresses were applied resulted in complex and often reversal of movements on faults.

Depositional patterns of stratigraphic units quite often are influenced by the previous tectonic events as evidenced for example by the location of paleo-stream channels, and the location of carbonate build-ups. Of more practical consequences, it is important to remember that the distribution of energy and mineral resources, especially where migration of fluids or gases is responsible for the concentration and accumulation of a commodity, is directly influenced by the tectonic framework of the rocks.

REFERENCES

- Berendsen, P., (in Press), Tectonic evolution of the Midcontinent Rift System in Kansas: Geological Society of America Special Paper.
- Clendenin, C. W., and Niewendorp, C. A., 1989, Reinterpretation of faulting in southeast Missouri: *Geology*, v. 17, p. 217-220.
- Denison, R. E., Lidiak, E. G., Bickford, M. E., and Kisvarsanyi, E. B., 1984, Geology and geochronology of Precambrian rocks in the central interior region of the United States: U. S. Geological Survey Professional Paper 1241-C, 20 p.
- Sims, P. K., and Peterman, Z. E., 1986, Early Proterozoic Central Plains Orogen: A major buried structure in the north-central United States: *Geology*, v. 14, p. 488-491.
- Van Schmus, W. R., 1992, Tectonic setting of the Midcontinent Rift System: *Tectonophysics*, 213, p. 1-15.
- Woelk, T. S., and Hinze, W. J., 1991, Model of the Midcontinent Rift System in northeastern Kansas: *Geology*, v. 19, p. 277-280.

NATIVE COPPER AND ASSOCIATED MINERALS IN BASALTS AT THE CALEDONIA MINE, WESTERN UPPER MICHIGAN

BORNHORST, Theodore J., Department of Geological Engineering and Sciences, Michigan Technological University, Houghton, MI 49931 and WHITEMAN, Richard C., Red Metal Explorations, Hubbell, MI 49934

The Caledonia Mine is located near Mass City in western Upper Michigan. It lies within an area of native copper deposits some 40 km southwest of the major deposits of the Keweenaw Peninsula native copper district. The Caledonia Mine produced about 3 million kg of native copper from 1863-1881 and 1951-1958. Since 1985 the mine has been tested by Red Metal Explorations. The Caledonia Mine provides access to continue studies of native copper mineralization while most of the native copper mines of the Keweenaw Peninsula are now flooded or closed permanently.

The Caledonia Mine intersects the Butler and Knowlton flow tops. These lava flows are part of a package of tholeiitic basalt lava flows up to 210 m in total thickness within the Portage Lake Volcanics. For most of its length the adit at the Caledonia Mine follows the brecciated amygdaloidal top of the Knowlton flow which dips at about 45° northwest. The average thickness of the stratabound Knowlton lode (flow top) is about 2.5 m but locally thickens to more than 6 m.

Native copper and an associated suite of secondary minerals fill amygdules and spaces between fragments in the brecciated lava flow top. Calcite is the most abundant secondary mineral. Quartz, epidote and K-feldspar are lesser in abundance and occur in subequal amounts. Prehnite, pumpellyite, and chlorite are present in small amounts. Native copper, in minor amounts, is associated with even less abundant native silver. Paragenetic sequence, based on filling of amygdules and open spaces, is K-feldspar followed by epidote and then calcite+quartz. Native copper tends to be more commonly associated with epidote, calcite, and quartz. Rarely is native copper abundant in areas with abundant K-feldspar.

No major differences exist in the abundance of secondary minerals averaged over the scale of 100's of meters. In contrast, over the scale of a few meters the distribution of secondary minerals is variable. A secondary mineral may be completely absent in one zone and extremely abundant in another. However, the meter scale variation does have a certain degree of regularity. In some areas the occurrence of secondary minerals is banded consistent with the progressive filling of open spaces indicated by amygdule paragenesis. The intensity of alteration is highest near both the hanging wall and footwall of the brecciated flow top lode. Distribution of secondary minerals also correlates with the occurrence of veins.

Veins are of two types. Some veins within the lode and extending into underlying massive basalt contain the same basic minerals as the lode, including native copper. These veins are

considered synchronous with lode formation whereas others are clearly late-stage. One vein of the former type is the target of current exploration. This particular vein strikes subparallel with the strike of the flow top but dips more steeply (about 80° for the vein) and has been traced for over 100 m. The vein is well developed in the footwall and below, but is hard to identify as it enters the lode. Within this vein the intensity of alteration varies from slight to very high. Original basalt can be completely converted to a green soft epidote+lesser chlorite rock, or a hard epidote+lesser quartz rock. Overall mineralogy and paragenesis is similar to the lode. The vein contains pockets of soft blue-green mineral identified as corrensite by XRD (mixed layered clay mineral with 50/50 chlorite and smectite unit cells stacked in perfect alternation). This vein has recently yielded outstanding world class quality specimens of crystalline native silver which was originally encased in white calcite (calcite was removed by acid leaching), and clusters of colorless calcite crystals internally laced with native copper in vugs. Several masses of native copper weighing over 100 kg and small groups of copper crystals originally encased in white calcite, some coated with very small cubic native silver crystals, have also been recovered during exploration. Massive datolite is associated with native copper, occurring on and within native copper. This vein is quite similar to veins described by Broderick (1931, *Economic Geology*, v. 26, p. 840-856) in the Baltic and Isle Royale Mines about 50 km northeast near Houghton. This steeply dipping vein is interpreted as a pathway for ascending hydrothermal fluids. Other veins are clearly late-stage and crosscut the native copper-mineralized lode at the Caledonia Mine. Late-stage veins containing calcite and laumontite are readily visible in the adit and are barren of native copper. Adularia is an additional late-stage secondary mineral that occurs in veins and in the lode. Veins played an important role in the deposition of native copper and associated minerals at the Caledonia Mine.

LITHO-TECTONIC AND MINERAL DEPOSIT MAPS OF THE SUPERIOR PROVINCE

K.D. Card, R.A. Frith, and K.H. Poulsen, Geological Survey of Canada, Ottawa

Litho-tectonic and mineral deposit maps of Superior Province were compiled at 2.5 million scale as part of a contribution to Decade of North American Geology (DNAG). Sources included published and unpublished maps compiled on a one million scale Digital Chart of the World base. Twenty maps were prepared, raster scanned and processed using Arc-Info software over a two month period. The Mineral Deposit Map was prepared from the Litho-tectonic Map and individual deposits were keyed by type, size and location from dbase files.

Geological units were grouped by age and tectonic type, based on U-Pb isochron ages, inferred depositional environments, and intrusive-orogenic sequence, in order to relate economic mineral deposits to environments and processes. Supracrustal rocks were assigned to late and early successor basins, accretionary complexes, calc-alkaline and tholeiitic arc sequences, and submarine tholeiitic-komatiitic mafic plain sequences. Where regional metamorphism is high, bulk composition, metamorphic and "unknown" affinity designations were used.

U-Pb GEOCHRONOLOGY OF THE SHEBANDOWAN GREENSTONE BELT, SUPERIOR PROVINCE, ONTARIO

Corfu, F., Jack Satterly Geochronology Laboratory, Royal Ontario Museum, 100 Queen's Park, Toronto M5S 2C6 and Stott, G.M., Precambrian Geoscience Section, Ontario Geological Survey, 933 Ramsey Lake Road, Sudbury, Ontario P3E 6B5

The Shebandowan greenstone belt, in the western Wawa Subprovince, is composed of Archean metavolcanic and metasedimentary rocks bound by a composite batholith to the south and impinging into the metasedimentary Quetico Subprovince to the north. An extensive geochronological study has been undertaken in order to constrain the stratigraphic relationships of the belt and date the formation of major plutonic suites, complementing an early U-Pb study carried out in the belt (Corfu and Stott 1986).

Geological and structural mapping had indicated the presence of two major volcanic assemblages, the north-facing Burchell assemblage in the northern part of the belt and the south-facing Greenwater assemblage to the south (Williams et al. 1991). Both assemblages were further subdivided into three cycles consisting of mafic and minor komatiitic volcanic successions capped by intermediate to felsic units. Our preliminary geochronological data show that most of these volcanic units developed within a relatively short period of time at around 2722 to 2718 Ma. This time frame also includes the crystallization of anorthosites and layered gabbroic bodies such as the Haines and the North Coldstream gabbros. A similar age has also been found for a felsic volcanic unit in the Saganagon belt to the southwest.

An age of 2733 Ma, determined in the previous survey for a porphyry sill intruding metabasalts in the northern part of the belt, remains unique and could indicate the presence of a tectonically interleaved older package or it could be a spurious age biased by a xenocrystic zircon component. A verification of this age is in progress. The only older unit found in this study is 2750 Ma tonalitic gneiss of the Northern Light Complex. Zircons with age between 2750 and 2900 Ma occur, however, as detrital components in younger sediments or as xenocrystic grains in granitic rocks.

A young volcanic episode at around 2695 Ma formed pyroclastic units located in northern segments of the belt. These units correlate with the previously dated 2696 Ma syn- or post D1 Shebandowan Lake pluton. A previous age determination of 2689 Ma for an alkalic volcanic rock is now supported by new ages of ≤ 2692 Ma for a volcanogenic unit of the Duckworth group and for a breccia in the Strawberry Hill area. An age of about 2693 was also obtained for the syenitic Tower stock. These Timiskaming-type units are coeval with emplacement of the 2690 Ma Saganaga pluton in the southwest, and hence with deposition of metasedimentary units of the Knife Lake assemblage in Ontario and Minnesota. The youngest ages of 2683 to 2680 Ma were obtained for syenitic to granodioritic phases of the Kekekuab, Icarus and Perching Gull Lake plutons. These ages overlap the less precise date of 2684 Ma previously obtained for the post-D2 Burchell pluton.

A maximum age of deposition of about 2682 Ma is provided by the youngest detrital zircon grains in a conglomeratic unit in the northeastern part of the belt. This unit represents the latest sedimentary succession known in the region, postdating deposition and deformation of much of the adjacent Quetico sedimentary rocks and of the Seine Group (Davis et al. 1989, 1990). Deposition of this late sedimentary succession probably reflects some of the latest tectonic adjustments occurring at the boundary between Wawa and Quetico subprovinces.

References: Corfu and Stott (1986). *Can J. Earth Sci.*, **23**: 1075-1082.

Davis, Poulsen, and Kamo (1989). *J. Geology*, **97**: 279-398.

Davis, Pezzutto, and Ojakangas (1990). *Earth Planet. Sci. Lett.*, **99**: 195-205.

Williams, Stott, Heather, Muir, and Sage (1991). *Ont. Geol. Survey, Spec. Vol. 4/1*: 484-539.

APPLICATION OF THE ALUMINUM-IN-HORNBLENDE BAROMETER ON EARLY PROTEROZOIC, POST-PENOKEAN PLUTONS, CENTRAL MINNESOTA.

DARRAH, K.S., and HOLM, D.K., Department of Geology, Kent State University, Kent, OH 44242; 216-672-4094; dholm@kentvm.kent.edu.

Archean and Early Proterozoic metamorphic rocks in central Minnesota record relatively uniform paleopressures of 5-6 kb associated with the Penokean collisional orogeny (1870-1830 Ma). These rocks are intruded by syn- (~1870 Ma) and post- (1812 Ma and ~1770 Ma) tectonic plutons, some of which occupy the cores of domal structures in the country rock (Southwick, and others, 1988). In order to assess the post-collisional uplift history of this part of the orogen we have applied the empirical Al-in-hornblende igneous barometer of Hammarstrom and Zen (1986) to estimate emplacement depths of the magmatic suite. This barometer correlates Al^{tot} content of magmatic hornblende linearly with crystallization pressure of intrusion. Of the six plutonic bodies sampled for this study, three contain the appropriate mineral assemblage required for the barometer and yield relatively uniform aluminum content from hornblende rim microprobe analyses. The results of microprobe analyses of the undated, moderately deformed Freedhem Granodiorite (KA-F), and the ~1770 Ma Isle (K-4) and St. Cloud Granites (MN-35) are recorded in Table 1. The barometer has been verified experimentally by Johnson and Rutherford (1989) and more recently by Schmidt (1992). The results of our data using both of these calibrations is given below.

Rock unit	Johnson and Rutherford, 1989	Schmidt, 1992
St. Cloud Granite	3.32 ± 0.5 kb	4.62 ± 0.6 kb
Freedhem Granodiorite	2.46 ± 0.5 kb	3.65 ± 0.6 kb
Isle Granite	2.30 ± 0.5 kb	3.47 ± 0.6 kb

The Johnson and Rutherford calibration was accomplished at temperatures of 740-780°C with $P_{tot} = P_{CO_2} + P_{H_2O}$, whereas the Schmidt calibration was carried out under water saturated conditions at temperatures of 700-655°C. To our knowledge there is no indication for the presence of a CO_2 -bearing fluid at the time of crystallization of these rocks, although such a thing may be, admittedly, difficult to evaluate. However, for independent reasons, we consider the pressures obtained by the Johnson and Rutherford calibration to give depth of intrusion estimates that are unreasonably low (i.e., less than 10 km for the Freedhem Granodiorite and Isle Granite). Recent thermochronologic data (see Holm and Lux, 1995 ILSG abstract, this volume) indicates that the intrusions were emplaced into country rock with ambient temperatures above 300°C. Considering an upper-crustal geothermal gradient in the range of 20-30°C/km, this indicates a minimum depth estimate of 10-15 km for emplacement of these plutons.

Using the calibration of Schmidt (1992), the St. Cloud Granite intruded at a pressure of 4.62 ± 0.6 kb. Assuming an average overburden density of 2.7 g/cc, this corresponds to a depth of ~17 km. However, the comagmatic (?) Isle Granite intruded at a pressure of 3.47 ± 0.6 kb corresponding to a depth of ~13 km. The fact that different intrusions of the ~1770 Ma magmatic suite yield different emplacement pressures suggests that magmatism occurred simultaneously with post-orogenic uplift. We interpret formation of the ~1770 Ma post-tectonic plutons in east-central Minnesota to have resulted from thermal relaxation of the internal zone of the orogen which remained overthickened for 50-70 Ma after collision. We envision thermal weakening and melt production as concurrent with the onset of significant post-orogenic uplift. Continued unroofing is suggested by the abundant 1760-1750 Ma Rb-Sr and Ar-Ar biotite cooling ages throughout central Minnesota. Intrusion and coeval uplift followed shortly by orogen-wide cooling are all consistent with an episode of orogenic collapse proposed by Holm and others (1993).

Although it has not been dated, the deformed Freedhem Granodiorite has been commonly considered a syn-tectonic pluton associated with the Penokean collisional orogeny. However, its shallower depth of emplacement relative to the post-tectonic St. Cloud Granite suggests to us that it is also post-tectonic. We interpret deformation features in the Freedhem Granodiorite (solid state foliation and cross-cutting shear zones), and perhaps also the country rock structural domes mentioned above, as features formed during uplift and collapse of the Penokean orogen.

Table 1. Results of Microprobe analyses on the Feedhem Granodiorite (KA-F), the Isle Granite (K-4), and the St. Cloud Granite (MN-35).

Sample	Si	Ti	Al	Mg	Ca	Mn	Fe	Na	K
KA-F-1	6.891	0.147	1.335	2.724	1.897	0.077	1.976	0.316	0.177
	6.915	0.143	1.329	2.708	1.876	0.071	1.978	0.362	0.156
	6.761	0.142	1.511	2.510	1.968	0.067	2.171	0.254	0.173
KA-F-2	6.843	0.148	1.424	2.597	1.952	0.069	2.015	0.317	0.182
	6.850	0.128	1.356	2.790	1.947	0.069	1.957	0.325	0.171
	6.822	0.147	1.439	2.641	1.921	0.074	1.999	0.359	0.181
	6.845	0.158	1.340	2.721	1.920	0.067	1.999	0.381	0.171
	6.832	0.160	1.401	2.709	1.875	0.073	1.986	0.361	0.185
K-4-1	6.819	0.142	1.455	2.659	1.890	0.086	1.972	0.390	0.191
	6.853	0.109	1.381	2.552	1.919	0.087	2.174	0.368	0.174
	6.808	0.117	1.470	2.488	1.942	0.082	2.158	0.380	0.171
	6.857	0.117	1.407	2.522	1.966	0.081	2.119	0.347	0.162
	6.927	0.083	1.360	2.642	1.902	0.078	2.072	0.347	0.146
K-4-2	6.891	0.104	1.391	2.539	1.923	0.086	2.125	0.314	0.159
	6.942	0.101	1.319	2.574	1.925	0.081	2.105	0.352	0.147
	7.008	0.086	1.290	2.587	1.943	0.072	2.030	0.344	0.145
K-4-3	6.991	0.091	1.275	2.633	1.920	0.081	2.041	0.357	0.141
	6.955	0.093	1.314	2.567	1.898	0.085	2.121	0.369	0.153
	6.974	0.073	1.320	2.640	1.987	0.093	2.064	0.319	0.143
MN-35-1	6.833	0.112	1.453	2.529	1.926	0.086	2.118	0.385	0.159
	6.590	0.224	1.640	0.242	1.867	0.052	4.420	0.394	0.266
	6.552	0.217	1.643	0.248	1.843	0.055	4.461	0.507	0.278
MN-35-2	6.580	0.212	1.627	0.221	1.851	0.056	4.500	0.431	0.265
	6.712	0.159	1.542	0.214	1.879	0.071	4.472	0.357	0.258
	6.735	0.143	1.530	0.234	1.885	0.061	4.448	0.388	0.255
MN-35-3	6.642	0.161	1.630	0.219	1.891	0.047	4.489	0.348	0.257
	6.594	0.184	1.628	0.210	1.784	0.077	4.502	0.598	0.270
	6.607	0.206	1.637	0.249	1.798	0.072	4.384	0.577	0.251

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Geochronology of the 1.1 Ga North American Mid-Continent Rift

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The Mid-Continent Rift (MCR) structure is underlain by one of the thickest crustal sections in North America and represents one of the great flood basalt provinces of the world with eruption of at least 1.5 million km³ of lava. The excellent preservation of much of the igneous stratigraphy provides an opportunity to test the resolving power of U-Pb zircon geochronology and to measure rates of plume-driven igneous processes in the Precambrian. Ages discussed below are based on zircon or baddeleyite analyses and are given with 95% confidence errors. The earliest igneous activity is represented by the emplacement of alkaline plutons such as the Coldwell complex (1108 $\pm$ 1 Ma)¹ and a syenodiorite within the lower North Shore Volcanic Group (NSVG, 1107.0 $\pm$ 1.6 Ma); as well as by the emplacement of tholeiitic sills such as the Logan sills (1109 $\pm$ 2 Ma)² and Nathan's layered series (1106.9 $\pm$ 0.6 Ma)³; and the eruption of felsic lava in the Powder Mill group (1107.5 $\pm$ 1.6 Ma), at the base of the Osler group (1108 $\pm$ 2 Ma) and in the lower part of the NSVG (1108.0 $\pm$ 2.1 Ma). All of these units are paleomagnetically reversed and appear to represent an intense but short-lived episode of mantle and induced crustal melting. A significant time gap occurs in NSVG stratigraphy between older paleomagnetically reversed and younger normal rocks. A sample from the Hovland lavas collected near the top of the reversely magnetized section gives 1107.6 $\pm$ 2.5 Ma, while a sample from the Chicago Bay lavas, near the base of the normally magnetized section, gives 1100.5 $\pm$ 1.9 Ma. This is followed by units aged 1097.9 $\pm$ 1.6 Ma, 1098.1 $\pm$ 1.5 Ma, 1098.5 $\pm$ 1.7 Ma and 1096.6 $\pm$ 1.9 Ma at higher stratigraphic levels, comprising a thickness of about 5 km. The Duluth layered gabbro complex was emplaced into the NSVG over a time span of at least 1099.3 $\pm$ 0.3 to 1098.6 $\pm$ 0.5 Ma³. The Portage Lake Volcanics (PLV) comprise over 4 km of basalts and are faulted at the base but appear to be structurally above the NSVG. Thick basalt flows near the base and top of the PLV give ages of 1096.2 $\pm$ 1.8 Ma and 1094.0 $\pm$ 1.5 Ma, respectively⁴. The PLV is overlain by sediments of the Copper Harbor Conglomerate which contain interlayered basaltic andesite flows, one of which gives an age of 1087.2 $\pm$ 1.6 Ma⁴. This age is coeval with emplacement of a felsic porphyry on Michipicoten Island at 1086.5 $\pm$ 1.3/-3.0 Ma⁵ and represents a final episode of volcanism. Thus, magmatism in the MCR shows a total time span of slightly more than 20 m.y. and appears to be confined to three main pulses, the most significant occupying a time span of approximately 7 m.y.

Paleomagnetic studies of MCR rocks have furnished the most reliable apparent polar wander curve for the Precambrian. Most sections show a single R-N polarity transition. The age of this reversal is constrained between the 1100.5 $\pm$ 1.9 Ma age of the normally magnetized Chicago Bay lavas and the age of a rhyolite sample from Agate Point, near the top of the reversely magnetized section of the Osler Group. This age was formerly reported as 1098 $\pm$ 4 Ma² from data which had to be corrected for substantial amounts of inheritance. Recent work on small, apparently inheritance-free zircon fractions gives a preliminary age of 1105 $\pm$ 2 Ma.

The interpretation of a single R-N transition within the MCR sequence is complicated by the presence of a R-N-R-N sequence at Mamainse Point. A volcanic unit from near the top of the lower reversed section gives an age of 1096.2 $\pm$ 1.9 Ma, implying a total of at least five reversals during development of the MCR. The Mamainse Point sequence may represent a short period oscillation of the geomagnetic field during the brief, geochronologically unresolved time between eruption of the NSVG and the PLV. A reversed gabbro dated at 1097.5 $\pm$ 3 Ma from a drill hole in Kansas⁶ may have also been emplaced during this period. The lower reversed section at Mamainse Point shows a coherent geochemical and isotopic trend^{7,8} implying that there are no significant age gaps over most of this sequence. If so, the fact that the reversed paleomagnetic poles determined from Mamainse Point show a high latitude similar to the 1108 Ma poles implies that at least the early part of the paleomagnetic polar wander path was dominated by

reversal asymmetry and there may have been very little continental drift. This might explain why plume-generated volcanism⁹ in the Lake Superior region persisted over a 20 m.y. period when the degree of apparent polar wander would suggest a continental drift of several thousand kilometers.

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DAVID BELL MINE POSTER DISPLAY

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The David Bell mine is located 35 km east of Marathon, Ontario on the Trans-Canada Highway. The mine lies within the Schreiber-White River Greenstone Belt and is jointly own by Teck Corporation and Homestake Canada Ltd.

Following the main ore zone discovery by consulting geologist David Bell in 1981, the first gold pour took place in May 1985 after two years of construction and underground development. Since then, the mine has been in continuous production extracting in excess of 2.0 million ounces of gold. Remaining reserves as of December 31st, 1994 are estimated at 4.9 million tonnes grading 10.85 grams per tonne.

The main ore group comprising of the "A" and "D" zone generally lies within the Moose Lake formation at the contact between quartz feldspar porphyry and metasedimentary rocks, often in close relationship with a mafic metavolcanic unit. The lower "C" zone lies within the laminated metasedimentary member of the Cache Lake formation. The ore horizons generally occur as tabular sheets striking at 102 degree and dipping between 50 and 61 degree north. Three distinct ore characteristics were observed in the underground workings and in the drill core.

The display consists of underground geology plans, longitudinal projection of the ore zones and a typical cross section. The sample collection includes a suite of representative mine samples and drill core specimens covering the ore horizons and wallrock lithologies.

IGNEOUS CHARACTERISTICS OF THE MATRIX TO THE FOOTWALL BRECCIA, NORTH RANGE, SUDBURY STRUCTURE, CANADA

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Much of the ore in the North Range of the 1.85 Ga Sudbury Structure is hosted by a discontinuous granitic unit known as the Footwall Breccia. Impact-generated embayments have provided topographical lows for the creation of a thickened heterolithologic breccia sequence overlain by an equally thickened Sublayer unit. The xenoliths within this breccia pile consist of randomly oriented, locally derived footwall gneisses as well as exotic clasts of diatexite, diorite, gabbro, pyroxenite, anorthosite, diabase, granite and Sudbury Breccia. Depending on their refractory properties, these inclusions may have diffuse or sharp contacts with the matrix, and may be represented by a diverse range of sizes. Quite frequently these breccia fragments are blanketed by elongate sulfide blebs, a texture which may have formed during the initial magma injection.

The matrix to these inclusions is a fine - to medium - grained granitic unit composed dominantly of grains of hornblende, pyroxene and large optically continuous grains of poikilitic quartz enclosing subhedral grains of plagioclase (An_{0-50}). Granophyric textures, consisting of intergrowths of quartz and fresh to saussuritized albite are very common, and increase in abundance toward the contact with the overlying norite. The matrix is also a major host to the Ni-Cu-PGE sulfides. These are represented predominantly by blebs of pyrrhotite, chalcopyrite, pentlandite and pyrite. Characteristic of the mineralized breccia is the increase in the occurrence of mafic minerals which may form halos around the sulfides.

Alteration of the matrix by interaction with formational fluids has locally produced a mineral assemblage of epidote, quartz, calcic amphibole, biotite ($X_{Mg/(Mg+Fe)} = 0.65$), chlorite ($X_{Mg/(Mg+Fe)} = 0.35 - 0.5$), garnet, titanite, magnetite and calcite (Epidote Zone, Fraser Mine). Fluid inclusion studies have shown that these fluids, which were driven by the heat of the cooling Sudbury Igneous Complex, formed this alteration assemblage and remobilized Cu, Ni, PGE, Au, Ag especially, at temperatures between 210 and 400 °C.

Petrographic study reveals the presence of quartz - albite (An_0) patches and veins with centrally located quartz - chlorite filled cavities. Quartz in the latter contains abundant fluid inclusions. Locally, original albite mineralization within the granophyric veinlets has been replaced by a pink potassic feldspar (orthoclase).

The mineralogy and textures that have been observed indicate that the Footwall Breccia was (1) formed by a magmatic process involving assimilation of footwall rock, and (2) subsequently altered by hydrothermal fluids related to the cooling Sudbury Igneous Complex.

VESICLES AND BRECCIA DUE TO INJECTION OF MAFIC MAGMA INTO
PARTIALLY LITHIFIED SEDIMENTS OF THE EARLY PROTEROZOIC IRONWOOD
IRON-FORMATION, WESTERN GOGEBIC RANGE, NW WISCONSIN

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Detailed mapping and petrographic analysis of iron- and silica-rich argillites of the Ironwood Iron-Formation and associated mafic and felsic intrusions was undertaken in the Western Gogebic Range near Atkins Lake, Wisconsin. The purpose of the study was to determine the nature, origin, and relationships of these rocks. In particular, we focused on the contact between the argillites and a sill-like mafic body. The contacts are marked by breccia zones that contain local areas of argillite clasts in vesiculated basalt matrix. In places the breccia resembles a peperite.

The study area is approximately 500 meters by 500 meters and was mapped at a scale of 1:1000. The rocks trend approximately N70°E and have an average dip of 50°NW. The argillite is thinly bedded to laminated and has a minimum thickness of 45 meters. Concordant with the argillite is a mafic body that has a fine-grained diabasic to medium-grained gabbroic texture. This mafic unit is approximately 50 meters thick. The contacts between the argillite and the mafic rocks are characterized by breccia zones up to 20 meters thick. The breccia consists of angular to subangular, tabular clasts of argillite up to 1 meter in diameter, some of which are bent. Most of the clasts are silica-rich, but iron-rich clasts have been observed. Garnets up to 5

mm in diameter are common and unique to the breccia zone. Locally, lodestone occurs in the iron-rich argillite at the contact with the breccia. Granitic dikes up to 1 meter wide intrude both the mafics and argillites. These granites are medium- to fine-grained with chilled margins.

Petrographic analysis was performed on 22 thin sections which included textural descriptions and 500 point counts per section. The argillite is composed of alternating layers of fine-grained magnetite, fine-grained biotite or actinolite, and recrystallized quartz. The mafic rock is composed primarily of medium-grained amphiboles with included plagioclase lathes, probably a relict ophitic texture. Magnetite is common. Preliminary geochemical data indicates a tholeiitic composition. The breccia consists of clasts that are composed of recrystallized quartz plus chlorite, or biotite plus garnet in a basaltic matrix that is locally vesiculated. Vesicles are infilled with chlorite, with or without quartz. Some vesicles are composed of quartz with chlorite cores. The granite is composed of medium- to fine-grained potassium feldspar, quartz, plagioclase, and minor amounts of biotite.

We infer that the argillites were deposited as a sequence of thin, alternating iron-rich and silica-rich layers. The sill-like mafic body intruded into these water-rich sediments while they were only partially lithified. Intrusion of the mafic magma into the water-rich sediments resulted in the formation of the breccia, i.e. peperite. The matrix of the breccia is locally vesiculated due to interaction of the mafic magma with water

derived from the sediments. We suggest that the breccia is not the result of a mafic lava flowing onto or into unconsolidated sediments because of: 1) development of a medium-grained gabbroic texture in the interior of the mafic body, 2) capture of angular, bent and tabular xenoliths in the breccia zone, and 3) formation of vesicles at the top and bottom contacts of the mafic body with the breccia. Garnets only occur in the breccia zones and most likely formed by contact metamorphism caused by intrusion of the mafic sill.

Significantly, emplacement of the mafic magma into partially lithified sediments does imply contemporaneous igneous activity and deposition of the Ironwood Iron-formation on the western end of the Gogebic Range. The mafic material now occurs as metadiabase and metagabbro, the result of later low-grade metamorphism. Granitic dikes that intrude concordantly to discordantly into the mafic and argillitic rocks have chilled margins and lack metamorphic features. In addition, the surrounding country rock does not appear to have been contact metamorphosed by the granitic intrusions. We infer that these dikes were emplaced after cooling of the mafic sill and the argillites, and are likely related to nearby Middle Proterozoic granitic rocks.

Neoarchean Transubprovince Depositional Systems: Temporal vrs Spacial Variability in Western Superior Province. Fralick, P.W., and Purdon, R., Department of Geology, Lakehead University, Thunder Bay, Ontario, P7B 5E1.

With the growing acceptance that plate tectonic processes similar to those operating today led to the amalgamation of Superior Province during the Late Archean comes the opportunity to use sequence stratigraphy techniques to analyze tectonic control of basin formation. Application of this technique and chemostratigraphy to four sedimentary basins in the Wabigoon, Quetico and Wawa Subprovinces of northwestern Ontario adds significantly to the tectonic interpretation of this region.

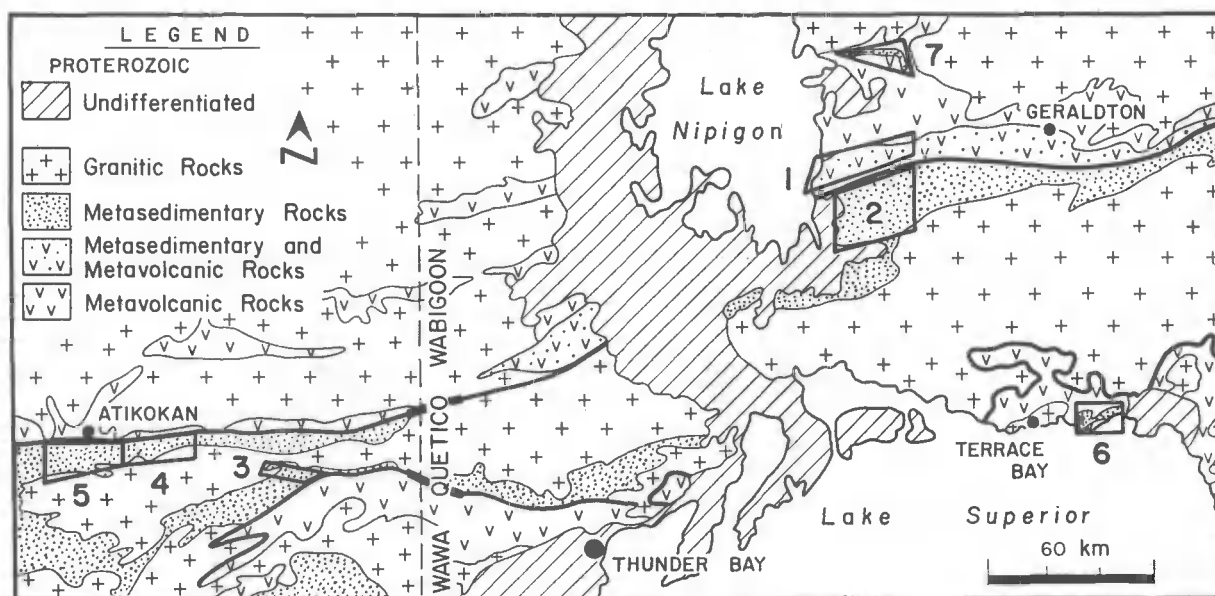
The Beardmore-Geraldton forearc basin, located in the southern Wabigoon Subprovince, and the Quetico trench formed a yoked system, with volcanoclastic sediment feed from the north (see Eriksson et al, 1994, and references therein). Braided fluvial channels delivered detritus to fan and braid deltas, which in turn rerouted it to the seafloor, building a submarine fan/ramp sequence in the distal portion of the forearc basin and trench. Sediment geochemistry of the forearc-trench assemblage is extremely consistent, implying that a similar source terrain existed laterally for 300 kilometres, or a single area provided most of the sediment. Immobile element ratios indicate that a calc-alkaline extrusive-intrusive suite present in the Onaman-Tashota Terrane supplied sediment to the forearc and the portion of the trench to its south. Immobile element ratios and zircon geochronology further indicate that the western trench received sediment from a volcanic-cratonic area to its north. This implies that geochemistry of the arc system was consistent from the continental arc in the west to the eastern oceanic? arc.

The sedimentary geochemistry of an interarc basin, present in the Wawa Subprovince east of Terrace Bay, is very similar to the Quetico trench. This basin is dominated by distal submarine ramp turbidites, while the Quetico to the north is composed of proximal ramp turbidites. These data imply that the depositional system overwhelmed the trench, overflowed onto the ocean floor and flooded into an interarc setting.

The fourth basin examined is in an intermontane setting within the Onaman-Tashota Arc Terrane. It was filled by a mostly subaqueous fan delta system with local sources of variable composition supplying the detritus. Sediment geochemistry confirms the variable nature of the source terrane and indicates large granitic batholiths present in the area were the major contributors. The difference in sediment source between the intermontane basin and other synvolcanic basins to the south can only be interpreted as a change in basin type through time reflecting cessation of volcanism in the area and emplacement and unroofing of later-stage batholiths. The basin may have been produced as a result of transpression but this conclusion awaits further structural studies.

FIGURE 1: Regional geology of portions of the Wabigoon, Quetico and Wawa Subprovinces, northwestern Ontario. Numbers refer to areas samples for sediment geochemistry (Table).

TABLE: Sediment geochemistry of the areas indicated on Figure 1.



	1 Wabigoon Forearc n = 7	2 Quetico Trench n = 8	3 Quetico Trench n = 5	4 Quetico Trench n = 10	5 Quetico Trench n = 14	6 Wawa Interarc n = 11	7 Wabigoon Intermontane n = 6
SiO ₂	64.1	64.0	64.7	64.4	64.1	64.0	71.8
TiO ₂	.54	.56	.56	.58	.50	.58	.32
Al ₂ O ₃	15.4	15.2	15.4	15.2	15.1	15.5	14.8
Fe ₂ O ₃	5.50	5.77	6.60	6.06	5.64	5.23	3.03
MnO	.09	.10	.09	.07	.12	.09	.05
MgO	2.73	3.07	2.76	2.92	2.51	3.00	.79
CaO	3.06	2.81	2.77	3.46	3.80	3.40	1.27
Na ₂ O	3.77	3.93	3.49	3.34	3.32	3.72	3.56
K ₂ O	2.08	1.68	2.36	2.10	2.16	1.95	2.44
P ₂ O ₅	.14	.15	.17	.14	.14	.19	.08
Ba	560	530	640	540	620	550	-
Co	24	24	-	-	21	-	-
Cr	106	170	175	142	119	-	-
Cu	35	48	-	38	50	-	-
Mo	1.1	1.1	-	-	3.2	-	-
Nb	5.2	5.9	-	6	6.0	5.9	-
Pb	85	94	-	15	26	-	-
Rb	68	73	83	66	57	48	-
Se	350	350	-	-	-	-	-
Sr	274	390	340	461	300	369	-
V	89	97	-	108	94	-	-
Y	10	10	14	16	13	13	-
Zn	61	59	78	78	78	-	-
Zr	103	103	142	138	127	101	-

1 and 2 - Fralick and Barrett, 1991; 3 - Sawyer, 1986; 4 - Williams, 1978;
5 - Stone et al., 1992; 6 - Purdon, in progress; 7 - Amukun, 1980.

CENTRAL MINNESOTA, U.S.A. CORE LOGGING AND ASSAY DATABASES

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This work includes the relogging and assaying of existing DNR Drill Core Library samples. The purpose is to provide data for land use planning and other geologic needs such as mineral exploration.

A total of 1241 sample sets representing samples from a total of 850 drill holes will be logged at the completion of this project, and approximately 1500 samples will be analyzed. Many of these drill samples have not previously been included on the DNR Drill Core Library Index (DCLI) (Ruhanen and Dzuck, 1994). Available historical information has filled many previous data voids for drill samples previously on the DCLI. The DNR Minerals Management Information Services continues to revise old data and incorporate new data into its ever improving DCLI.

Drill samples encountered include Proterozoic and Archean rocks, with scattered Paleozoic, Mesozoic, lateritic weathering products, and glacial materials. Of the lithologies encountered, the iron formation (Proterozoic Algoman type?) related rocks (including metavolcanic schists) are typically deformed, metamorphosed (typically low grade), altered, and recrystallized. Other rocks include gneiss, Keweenawan rift material, and some schists that may represent the continuation of the Wisconsin Volcanic Terrane that hosts Cu-Zn-Au deposits.

Results for the 1300 analyzed samples have been received from Bondar-Clegg & Company Ltd. of Ottawa, Ontario. Besides being (in general) anomalously high in Mn and Fe, samples also had anomalous Ba, As, Hg, F, Li, Nb, Zr, and rare earths. In general samples with higher TiO₂ also had higher K₂O and Al₂O₃. Anomalous Zn values (with visible sphalerite) include DDH K-1 in T47N R20W Sec 22 with a 5' sample containing 2.25% Zn. This occurred in deformed graphitic sulphide phyllite with minor chloritic sericitic metatuff. Drilling at the Arrowhead Mine (graphite) in T48N R18W Sec 32 produced brecciated graphitic sulfide schist samples with several Zn values over 1300 ppm (high of 1916 ppm). Samples from several drill holes in T43N R32W Sec 12 had anomalous base and precious metals. Perhaps the most interesting values came from drill hole 109. This 5' sample contained 1383 ppb Au, 1339 ppb Pd, 1156 ppb Pt, and 1343 ppm Zn. Another drill sample contained 2.3 ppm Au. Samples (one of carbonate, magnetite, silicate iron formation) from two other drill holes in this area had Cu values of 1791 and 1200 ppm respectively. In T46N R29W Sec 9, DDH 310 contained a sample with chert(?), hematite, quartzite(?) iron formation with a Cu value of 1622 ppm, and an adjacent chert, goethite, hematite, Mn oxide(?) iron formation sample with the highest Li value (1145 ppm). The highest As value was 1362 ppm in tuffaceous carbonate, chert, goethite, magnetite, red hematite, silicate, sulfide iron formation (with tourmaline?) in DDH 280, located in T46N R29W Sec 2. The analyses above without lithologies indicate that they came from powdered samples without identifiable rock fragments. Pending XRD work may provide some answers. =\Other locations also contained anomalous samples.

The data indicates that hydrothermal processes were active within the study area, and that there may be a high probability for undiscovered economic mineralization.

Reconnaissance drill core logging information has been created and stored as digital files. This includes basic information about rock types, alteration, and mineralization. Each database record corresponds to a unique drill hole and footage interval. A separate "comments" database contains a brief synopsis of each drill hole and notes on unusual features. Other "related" data files include the DCLI, chemical analyses, sample information, and core geophysical measurements. Combined, these databases form an abundance of available information for possible synthesis by users.

The logging databases were "constructed" using a data manipulation system called WATFILE/Plus and Software Carousel. This allowed six databases to be open at one time, and still allow for very rapid database switching, queries, data entry, and editing. The six databases consist of a geographic portion of the

DCLI, the logging database, the logging comments database, the lithologic code database, the alteration code database, and the database containing sampling information. While not being truly "relational", the individual WATFILE databases were constructed with the common fields necessary for linking after importing into a relational database.

The methodologies for data synthesis and utilization will be dependent upon hardware and software limitations, and the ingenuity of the user. One hope for a future product will be a Paradox run-time module that will make the data useable to those who do not have their own database software. Such "module" users should be aware, however, that any packaged data queries will be limited to those of the developer's preconceived notions. Usage of this data can make geologic visits to the Drill Core Library more efficient. The database also allows preliminary work to be done BEFORE a visit.

As in any database "development", certain ideas were used in this database formulation: 1) TRY to convey to the users HOW it was put together and what its limitations are; 2) TRY to be consistent in application and usage; 3) Create the data to support anticipated queries; 4) Convey uncertainty as best possible when it exists; 5) Lithology, alteration, and mineralization searches and queries are to make use of text string matches; 6) Be cognizant of the importance of proper spelling and spelling variations; and 7) Be as quantitative as possible within the context of the data structure. THE MOST IMPORTANT IDEA IS TO LET THE USER MAKE THE MOST EFFICIENT USE OF THE DATA. . . TO MAKE THE MOST OF THE DATA WITHOUT BEING LED ASTRAY!

As in the "utilization" of ANY database, certain concepts should be embraced; 1) Become familiar with the actual data, to see how it was used, to see its limitations, and if possible, see how well it actually represents that which it supposedly describes; 2) Make queries that are supported by the data; 3) In the case of descriptive data, be aware that there may be alternative language with similar meaning that should be included in making data queries; 4) Be cognizant of the specificity of your queries relative to the specificity of your data; and 5) Queries done on the "logging" database should also be done on the "comments" database.

An additional 2600 sets of drill samples exist from the study area of Central Minnesota and have not been logged. These represent samples from approximately 1600 drill holes. Many of these samples are drill core. Most of these samples were originally drilled in the search for iron and manganese in the Cuyuna Iron Range area during the first half of this century. A lesser number of samples were drilled for base metal, uranium, precious metal, or diamond exploration. Additional samples were drilled for regional geologic or engineering information.

This work will be published in July, 1995, with the data available digitally in a variety of formats.

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Ruhanen, R. W., and Dzuck, A., 1994, 1994 Drill Core Library Index: Minnesota Department of Natural Resources, Minerals Division, 218 pages.

CURRENT INVENTORY OF MICHIGAN'S GEOLOGICAL CORE AND SAMPLE REPOSITORY AT MARQUETTE

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The Geological Survey Division (GSD) of the Michigan Department of Natural Resources (DNR) maintains the Geological Core and Sample Repository at Marquette, Michigan. This "Rock Library" collection of core, cuttings and samples currently represents 62 of the 83 counties in the state. The materials are available for study to help understand the geology and mineral resource potential of the state.

The collection continues to grow in an effort to better represent the geology of the state. Materials are submitted to the Repository from a number of sources: 1) state metallic and nonmetallic mineral leases; 2) various state sponsored projects; 3) company donations; 4) other state and federal government agencies, such as the U.S. Bureau of Mines.

Since January 1994, cuttings from all selected new oil and gas wells drilled in Michigan have been sent to the Repository. These cuttings account for much of the material currently being received.

The most significant recent addition was the early release of confidentiality of the deepest all-cored Mineral Well in March, 1995. AMOCO Production Company released the confidentiality on the core, well logs and file data for their St. Amour #1-29 and #1-29R test holes. The #1-29R is a 7,238 foot hole that was drilled in late 1987 to learn more about the Midcontinent Rift. It was located southeast of Munising, near Wetmore, in Alger County in the Upper Peninsula. The hole went through 110 feet of glacial drift and entered bedrock in the Paleozoic aged Autrain Formation of Ordovician time. The hole ended in Precambrian aged Portage Lake Volcanics of Keweenawan time. This core should be of interest to geologists from academia, the oil and gas industry, and the mineral exploration industry.

On March 31, 1995, the Repository collection contained 766 complete drill hole cores totaling 246,679 feet; drill cuttings from 440 holes representing 491,735 feet of drilling, 424 holes represented by abbreviated core from 131,380 feet of drilling, 2,229 feet of represented overburden drilling, and many boxes of miscellaneous materials (chip samples, soils, outcrop samples, assay pulps, etc.). This gives a collection total of 1,685 drill holes representing 872,023 feet (165 miles) of drilling plus numerous boxes of miscellaneous materials.

The GSD's Metallic Mine Map and Data Collection is also stored at the Repository. This collection also helps in the understanding of the geology and mineral resource potential of the state, as well as being an aid to public safety and land use planning. It is a record of potential mine subsidence areas of the state which should be avoided when construction is planned.

The Repository is open for visitors by appointment to study the contents. Some sampling and loans of material can be arranged for on a case-by-case basis. Copies of data derived from the use of the collections are to be submitted to be made part of the public record for future use. For information or an appointment, call Bill Swenor or Milt Gere at 906-228-6561.

The GSD also maintains all oil and gas well logs and thousands of selected well cuttings for oil and gas wells drilled prior to 1994 in Lansing. Water well records for the entire state are kept in Lansing by the GSD, too. Call 517-334-6907 for information. Copies of all Upper Peninsula, Region I, water well records and well cuttings from 610 selected water wells are maintained by the GSD at the DNR's District 3 Office near Escanaba. Call Frank Chenier at 906-786-2351 for more information.

GEOLOGY OF THE NORTH SHORE STATE PARKS

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The bedrock geology of the nine State Parks along Minnesota's North Shore of Lake Superior has been mapped, with funding from the MN Department of Natural Resources. Recent mapping by the author augments earlier work published by the Minnesota Geological Survey. Notable features of the surficial geology, such as abandoned shorelines, deltas, and stream channels, are also mapped. For some parks, the recent work of B. A. M. Phillips (personal communication, 1994 and Phillips et al., 1994) on surficial features has been very useful. Along with the geologic maps, an account of the geologic history of the region was prepared, as well as a description of the relation of geology to the scenery in each park. The project is aimed at publication of a book for the general public.

The parks at the two geographical extremes, Jay Cooke and Grand Portage, are underlain principally by Lower Proterozoic (≈ 2.0 billion years old) metasedimentary rocks (cut by 1.1 b.y. diabase dikes) whereas the remaining seven are underlain by 1.1 b.y. volcanic and intrusive rocks of the Midcontinent Rift System.

The major scenic features of the North Shore are a legacy of its geological history, coupled with the effects of differential erosion of rock layers or intrusions of differing resistance. The "Sawtooth Range" is the result of the slow erosional etching out of thick, resistant lava flows and sills that are interlayered with more easily eroded sandstones and thinner lava flows, all tilted gently toward the lake. The highest eminences near the lake, beside the thick Palisade rhyolite flow in Tettegouche S.P., are made of concentrations of large (10-100 m across) blocks of resistant anorthosite, carried up in diabase magma from the base of the earth's crust, now enveloped in the solid diabase. Examples are in Split Rock Lighthouse State Park and Carlton Peak, Temperance River S. P.

Thick sequences of volcanic rock underlie many of the parks. For instance, Cascade River S.P. includes a nearly 2200-foot sequence of basalt flows and sandstone; Judge Magney S.P. is underlain by an estimated 4800 feet of interbedded basalt and rhyolite flows. Some of the large rhyolite flows, such as in Tettegouche and Judge Magney, were erupted in violent, explosive events much larger than the Mt. St. Helens (1980) or Pinatubo (1991) eruptions. All of these volcanic rocks were erupted on a broad, gradually subsiding continental plateau.

The river gorges and many other interesting North Shore features were produced during and since the melting of the last Pleistocene ice sheet, when the west end of the Lake Superior basin was occupied by a deep, ice-dammed lake whose level fell in stages between 11,000 and 8000 years ago. Some of these features include abandoned shorelines, deltas, and river meanders (Jay Cooke S.P.) and channels (e.g. Judge Magney). Waterfalls developed where resistant igneous rocks were encountered (Split Rock, Tettegouche, Cascade, Grand Portage S.P.), or columnar jointing in basalt flows localized erosion (Gooseberry Falls).

ARE THE MAJOR THRUST FAULTS OF THE MID-CONTINENT RIFT AND THE KAPUSKASING ZONE PART OF THE SAME TECTONIC ZONE?

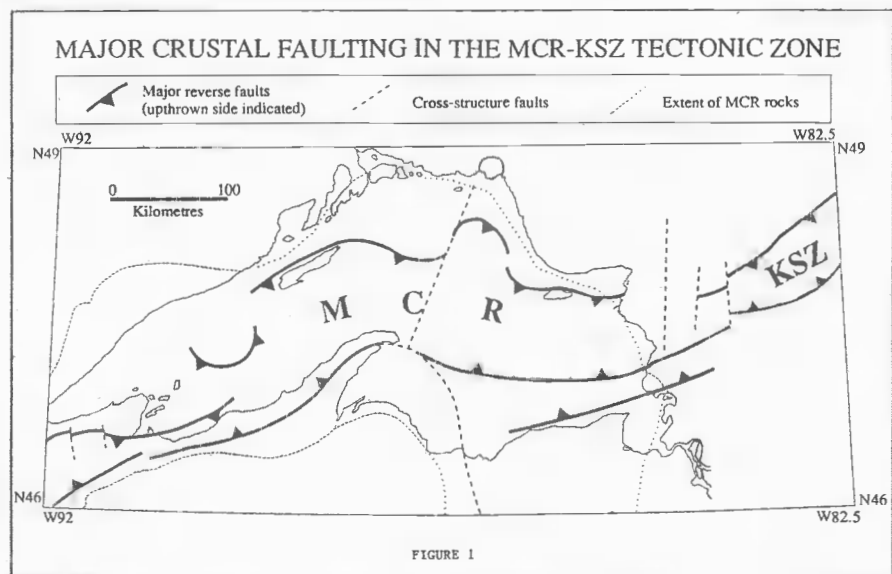
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Regional variations in paleomagnetic polarity and feldspar clouding in the 2.45 Ga Matachewan dyke swarm have been used to delineate major faults across which the southern Superior Province has been differentially uplifted by about 10 km or more¹. These observations, originally used to define NE-trending faults associated with the Kapuskasing zone (KZ)¹, have been extended to a region lying between the southern end of the KZ and the 1.1 Ga Lake Superior Basin. Here changes in regional magnetic polarity have defined two new faults and extended a third one. The new results suggest that towards the SW, the KZ is progressively depressed and displaced sinistrally by a system of N-S trending faults, the western one of which is the Agawa Canyon fault. Changes in feldspar clouding intensity between dykes suggest that the blocks between the faults also have been tilted to the east. The new data indicate that the NW faulted margin of the KZ continues westwards to within about 60km of the Lake Superior eastern shoreline. Here, gravity, magnetic, and geological studies have identified several ENE-trending reverse faults with vertical displacements up to several kilometres². Magnetic, reflection seismic and bathymetric data from eastern Lake Superior suggest that two of these faults represent an easterly continuation of the Isle Royale and Keweenaw faults between which the inversion of the Mid-Continent Rift (MCR) has taken place to form a pop-up structure. Lithoprobe seismic data suggest that the NW margin of the KZ dips to the SE³, and hence that the KZ also represents a pop-up structure. The foregoing evidence suggests that the reverse faults of the KZ and MCR are part of the same structure (Fig. 1) and together define a major ENE to NNE-trending compressional tectonic zone more than 2000 km long. Parts of this zone have experienced periodic reactivation since the Archean, the last significant phase of which was in response to the Grenville orogen at about 1050 Ma.

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- 2: Manson, M.L. and Halls, H.C., 1994. *Can. J. Earth Sci.*, 31, p. 640;
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THERMOCHRONOLOGY OF CENTRAL MINNESOTA REVISITED: IMPLICATIONS FOR THE POSTCOLLISIONAL EVOLUTION OF THE PENOEKIAN OROGENIC BELT.

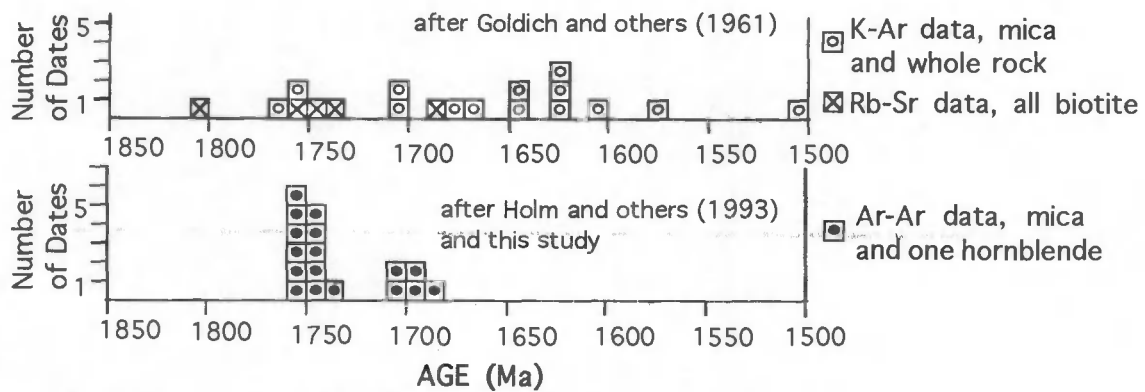
HOLM, D.K., Department of Geology, Kent State University, Kent, OH 44242 (216-672-4094; dholm@kentvm.kent.edu); and LUX, D.R., Department of Geological Sciences, University of Maine, Orono, ME 04469.

Rocks exposed in central Minnesota represent deep-seated metamorphic and plutonic rocks of the internal zone of the Penokean collisional orogen (1870-1830 Ma). In their classic study of the geochronology of Minnesota, Goldich and others (1961) obtained Rb-Sr and K-Ar mica and whole rock ages from central Minnesota in the range of 1500-1800 Ma (see histogram below). The wide scatter in ages has hindered their interpretation, although the relatively older Rb-Sr dates have been attributed to the onset of regional post-Penokean uplift whereas the younger K-Ar dates are commonly considered to reflect an orogen-wide, low-grade metamorphic resetting event. In this study, we have dated mica separates from Archean and Early Proterozoic metamorphic and plutonic rocks from central Minnesota using the modern $^{40}\text{Ar}/^{39}\text{Ar}$ incremental heating technique. Mica separates collected across a >130 km northeast-southwest transect in central Minnesota yield two distinct age populations (see histogram below). The younger population (1680-1700 Ma) represents data obtained solely from samples collected within the McGrath gneiss dome. The older population represents data obtained from samples collected outside the dome (both to the north and southwest). They include the Archean/Early Proterozoic Hillman migmatite, the Early Proterozoic Little Falls and Denham Formations (and unnamed equivalent rocks to the north), and Early Proterozoic plutons which are intrusive into the metamorphic rocks.

These results provide important new information on the post-collisional thermal history and tectonic development of the Penokean orogen. In central Minnesota mica $^{40}\text{Ar}/^{39}\text{Ar}$ ages obtained from late and post-tectonic plutons are concordant with mica ages obtained from the Penokean-metamorphosed country rock. This suggests that post-Penokean plutons (1812-~1770 Ma?) thermally equilibrated with the country rock at temperatures above 300°C. Emplacement of the post-tectonic magmatic suite was followed by an episode of regional uplift and cooling through ~300°C just prior to ~1755 Ma. We propose that the dome and basin structural style, which appear from aeromagnetic data to be associated with the plutons, may have developed during uplift. We further speculate that dome formation may have been triggered by the plutonic activity and that the intrusions were a contributing factor to continued isostatic uplift. The remarkably uniform ages obtained from rocks outside of the McGrath gneiss dome suggest moderate to relatively fast uplift rates (see Holm and others, 1993). We interpret the younger ages obtained from within the McGrath gneiss dome as reflecting the time of dome formation during yet another younger episode of uplift.

Research in the previous decade has shown that Phanerozoic orogenic belts developed during convergence are commonly structurally modified during their demise by gravitational collapse. In like manner, we propose that crust thickened at 1870-1830 Ma during the Penokean collisional orogeny underwent structural modification during its collapse from the mid to late 1700 Ma (Holm and others, 1993). In Minnesota, collapse of the orogen appears to have begun around 1760 Ma shortly following an episode of magmatism. We argue that the magmas may have contributed to thermal weakening of an overthickened crust which led to collapse driven by gravitational instability. Orogenic collapse was apparently episodic with significant pulses occurring at ~1755 Ma and at ~1700 Ma.

As noted by Holm and others (1993), the late low-grade metamorphic event widely recognized in Wisconsin and Michigan apparently affected these rocks to a much lesser extent than previously thought.



Comparison of age histograms of thermochronologic data from Archean and Early Proterozoic rocks of central Minnesota (both histograms cover the area from southwest of Little Falls to near Moose Lake).

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EXTENSION OF THE WISCONSIN MAGMATIC TERRANES INTO THE MINNESOTA SEGMENT OF THE PENOKEAN OROGEN

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Previous work established that the Wisconsin and Minnesota segments of the Early Proterozoic Penokean orogen are generally equivalent, and strata north of the Niagara fault in Wisconsin have been correlated with those north of the Malmo structural discontinuity in Minnesota. The Niagara fault separates supracrustal rocks of the Marquette Range Supergroup to the north, which have continental chemical affinities, from those of the Wisconsin Magmatic Terranes (WMT) to the south, which have volcanic arc compositions. Parts of the Marquette Range strata are analogous with the epicratonic rocks of the Mille Lacs Group north of the Malmo discontinuity in Minnesota. However, little was known of the rocks south of the discontinuity, largely because outcrops are rare. Much of that bedrock was interpreted as Penokean granitoid intrusions, although geophysical signatures imply that rock types and structures are more diverse. Recent results of test drilling and geophysical studies provide new insight on the southern part of the Penokean orogen.

Our current work south of the Malmo structural discontinuity in Minnesota divides the area into five geophysically distinct, arc-shaped terranes. The arcuate pattern is inferred to represent northwest-verging tectonic imbrication during the Penokean orogeny; however, details about individual terranes and their bounding structures are obscured by cover of Quaternary deposits and thick saprolite, by post- and syn-kinematic plutons which make up as much as 50 percent of the subcrop, and by several generations of faults. Nevertheless, some elements of the Penokean orogen can be deciphered. The *McGrath terrane*, on the north, is a dome of Archean McGrath Gneiss mantled by clastic and volcanic strata of the Denham Formation. It is separated from the Hillman-Little Falls terrane to the south by a sharp geophysical break here named the Mille Lacs discontinuity. The *Hillman-Little Falls terrane* is composed of foliated tonalitic to granodioritic rocks of the Hillman Migmatite and the Sartel Gneiss, which are metamorphosed to the amphibolite to granulite facies, and the Little Falls Formation—a pelitic schist containing biotite, staurolite, garnet, and sillimanite. The metamorphic rocks of the terrane are intruded by at least two generations of post-metamorphic plutons including granodiorite dated at 1868-1869 Ma, and several oval to irregularly shaped granitic bodies in the range of 1770-1812 Ma, together with many small plug-like intrusions of unknown age which vary in composition from peridotitic to charnockitic. The arcuate western edge of the Hillman-Little Falls terrane appears to represent the western termination of Early Proterozoic thrust sheets, and is marked by sharp geophysical contrast between Proterozoic metaclastic rocks and Archean granitoid gneiss. The *Milaca terrane* is the most lithologically diverse, and from an exploration perspective, perhaps the most promising. The eastern part of the terrane is composed of a variety of plutons separating screens of older supracrustal rocks. These older rocks include exposures of basalt and anorthositic gabbro, and several drill holes intersected amygdaloidal and porphyritic basalt and dacitic to andesitic crystal-lapilli tuff. All are metamorphosed to at least greenschist facies, and intense shearing is locally evident in both plutonic and supracrustal rocks. The western part of the terrane is almost entirely obscured by post-kinematic plutons. The narrow *Princeton terrane* contains schistose rocks of undetermined protolith and granite. The terrane is sharply bounded by ENE-trending geophysical discontinuities that intersect linear anomalies trending eastward. The geophysical pattern of the southernmost *Becker terrane* is marked by semicircular anomalies that suggest the presence of gneiss domes, and samples from several drill cores confirm that gneissic rocks are present, together with strongly schistose rocks of supracrustal protolith.

Correlation between the two segments of the orogen across the intervening Middle Proterozoic Midcontinent rift system, based on gross attributes of the structural terranes, is shown schematically on Figure 1. These attributes are inferred from outcrop and drill-hole data in Minnesota, published geologic maps of Wisconsin, and derivative geophysical maps of both states. We depict the bounding structures between terranes on the Minnesota side of Figure 1 as relict thrusts. This inference is speculative because geophysical modeling indicates that most contacts dip steeply, and that most sources within individual terranes extend to depths of 2-5 km. However, drill cores of some supracrustal and gneissic sequences show much shallower dips, locally in the 30-50° range, and we infer that many of the anomalies are bounded by steep faults and plutons. The most compelling correlation is based on strong lithologic (and geophysical) contrasts across the Niagara fault and its Minnesota analog—the Mille Lacs and Malmo discontinuities. These faults separate strata of continental affinity to the north that typically lack plutons, from volcanic

rocks to the south that are cut by abundant post- to syn-tectonic granitoid intrusions. Previous work by Southwick and Morey (1991) inferred a south-dipping subduction zone along which Penokean rocks were thrust northwestward over continental crust of the Superior craton. If this is correct, the boundary between pluton-bearing and pluton-absent rocks—the Niagara and Mille Lacs-Malmo structures—may represent the southernmost extent of continental crust beneath Penokean strata.

The presence of volcanic and volcanoclastic rocks in the Milaca terrane invites correlation with the Pembine-Wausau terrane of the WMT. The Princeton terrane is inferred to be an early, complex shear zone separating the supracrustal rocks of the Milaca terrane from gneisses of the Becker terrane. The Princeton, therefore, may be correlative with the Eau Plaine shear zone which separates the Pembine-Wausau terrane from Proterozoic and Archean gneisses of the Marshfield terrane to the south. Correlation of the Hillman-Little Falls terrane is more enigmatic, because it is intruded by syn- and post-tectonic plutons like the WMT and Milaca terrane, but it also contains migmatitic gneiss (of unknown age) and pelitic schist like the terranes north of the Niagara fault. We tentatively suggest that the Hillman-Little Falls is a hybrid containing lithic and structural elements of the terranes both north and south of the Niagara fault. It may not have an analog in Wisconsin, or it may be represented by a poorly exposed tectonic sliver.

Correlating segments of the orogen across the Midcontinent rift is not only of scientific interest, but also of economic interest because the WMT host deposits of base-metal sulfides and associated precious metals, including those of the Ladysmith mine. In an earlier paper (*Minnesota Prospector*, January 1995), we asked the question "can the Early Proterozoic Wisconsin Magmatic Terranes be traced into Minnesota?" The simple answer is a guarded "yes."

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ACKNOWLEDGMENTS

Test drilling, outcrop mapping, and geophysical studies were supported in large part by the Minnesota State Legislature on the advice of the Minnesota Minerals Coordinating Committee.

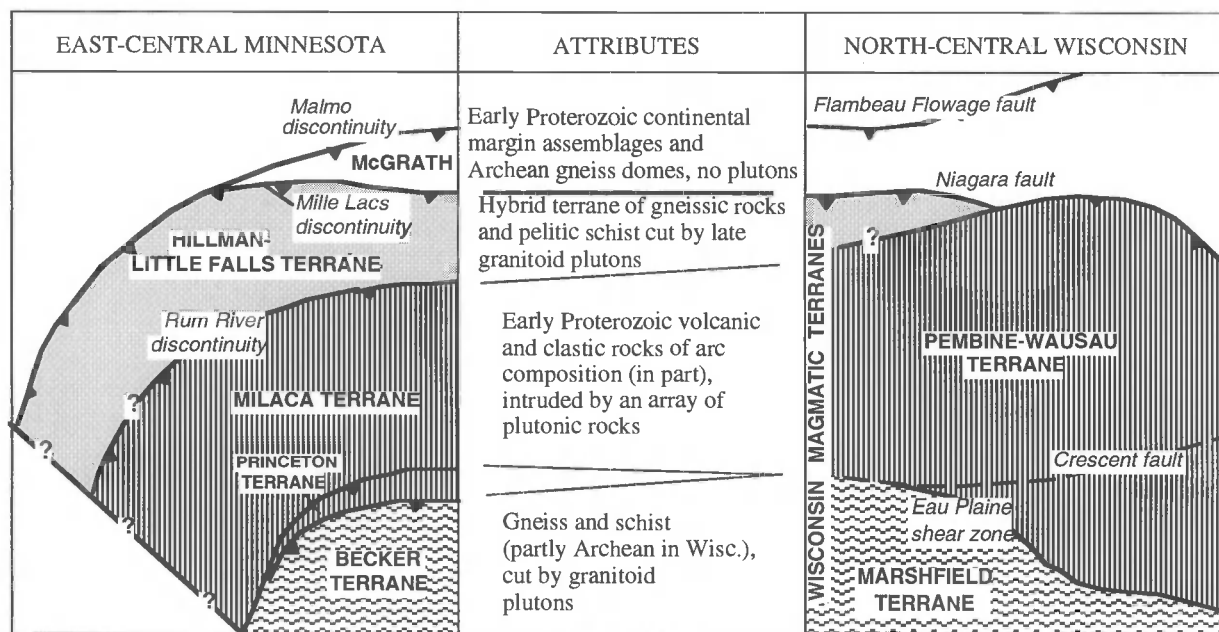


Figure 1. Schematic comparison and proposed correlation of major structural terranes of the southern Penokean orogen in east-central Minnesota with those of north-central Wisconsin.

TITANIUM ORE POTENTIAL OF GABBROS: EXAMPLES FROM WESTERN FINLAND

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Early Proterozoic Svecofennian gabbros are being explored for ilmenite by the Geological Survey of Finland. Two different types of Ti-enriched gabbros occur at Pohjanmaa, western Finland. Subeconomic, low grade titanium deposits, with ilmenite and apatite as major ore minerals and minor magnetite, are hosted by small- to medium-size layered gabbros located between late orogenic and synorogenic granite complexes (Kauhajoki).

Potentially economic titanium ore, with ilmenite as the major ore mineral and vanadiniferous magnetite as a minor ore mineral, is hosted by a small layered mafic intrusion located 200 km north of Kauhajoki in the western margin of the synorogenic Mid-Finland Granite Complex (Kälviä).

Kauhajoki gabbros occur as lenticular bodies along the eastern contact of the late orogenic Lauhanvuori microcline granite. These gabbros were previously studied as a possible source for phosphorous. The large Perämaa deposit, averaging 5.8 % apatite, belongs to the same gabbro province. The best Ti-enriched gabbro of this type is at Kauhajärvi. Here apatite and oxides occur together. Most of the Ti at Kauhajärvi is sited in ilmenite. Disseminated oxides are more abundant in melagabbro-norites at the bottom of the steeply dipping intrusion. Coarse-grained plagioclase-rich gabbro with thin anorthositic layers composes the roof of the intrusion. Kauhajärvi contains grades of 4 to 7 % apatite and 7 to 12 % ilmenite, but is subeconomic, partially because of thick overburden. The total amount of apatite and oxides is normally between 18-22 wt.% and the ilmenite/magnetite ratio is about 2. There are also magnetite-rich layers with slightly increased ore grade, however, these layers have much lower ilmenite/magnetite ratios (0.5-1.2). Good quality concentrations of ilmenite and magnetite, as well as the beneficiation of phosphorous, are indicated by metallurgical tests.

The Koivusaarenneva ilmenite deposit at Kälviä is hosted by an unexposed 3 - 5 km long and 500 m thick, almost vertical sill-like intrusion surrounded by tonalites and granodiorites, at the contact of the mid Finland Granite Complex and the Sykäräinen Volcanic Belt. The intrusion is clearly identified from aeromagnetic maps. Detailed magnetic and gravimetric surveys have been used for locating drill holes. The gabbro body is cut by fault zones and is divided into two main units along strike with significant displacement. The intrusion consists of 5 lithostratigraphic zones with gradual contacts. From bottom to

top these zones are 1) heterogenous lower barren uralite gabbro zone; 2) main ore zone consisting of disseminated ore in gabbro, massive ore layers, and metapyroxenite layers; 3) zone of barren uralite gabbro; 4) layered zone consisting mainly of ilmenomagnetite disseminated ore in gabbro and barren uralite gabbro layers; and 5) mainly coarse-grained uralite gabbro. The most mafic rock in the intrusion is almost totally uralized metapyroxenite, which exists as thin layers in several zones, but mostly in the main ore zone. Coarse-grained plagioclase cumulates of the uppermost zone contain minor enrichment of apatite. Prominent enrichment of phosphorous, 2 to 5 % apatite, exists in some zones of ilmenite-barren medium-grained uralite gabbro.

The ore zone has been followed for over 2 km along strike. The ore is both massive and disseminated. The massive ore is up to 15 m thick and contains 23 to 52 wt. % ilmenite, 4 to 18 wt. % magnetite and 1 to 2 wt. % iron sulphides. It is surrounded by a few tens of meters of ilmenite-rich disseminated oxides, averaging over 10 % ilmenite with minor vanadiferous magnetite. Massive ore is hosted by almost totally uralitized metapyroxenite, whereas disseminated ore is mostly in uralite gabbro.

Common features of Ti-enriched gabbros of western Finland are small size, distinct layering, compositional range from minor pyroxenite, through dominant gabbro-norite, to coarse-grained leuco-gabbro with only thin anorthositic layers. Economically, the most significant feature is that Ti is sited in ilmenite and there is only a minor amount of ilmenomagnetite. Geochemically, the Ti-gabbros are characterized by enrichment of phosphorous.

DEPOSITIONAL SYSTEMS ASSOCIATED WITH THE 3.0 GA. FINLAYSON AND LUMBY LAKE GREENSTONE BELTS, NORTHWESTERN ONTARIO

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The Late Archean Superior Province of the Canadian Shield is known to consist of alternating linear belts of granite-greenstone and metasedimentary terrains. An accretionary model has been suggested, involving island arcs and paired metasedimentary complexes colliding with older cratonic masses (Langford and Morrin, 1976). Support for this model has come from recent studies of the Quetico metasedimentary belt and portions of the neighboring Wabigoon Subprovince to its north (Williams, 1986, 1987; Devaney and Williams, 1989; Barret and Fralick, 1989; Fralick et al., 1992). Quetico trench sediments are constrained in age between approximately 2710 to 2690 Ma (Davis et al., 1990).

The interior of the Wabigoon Subprovince is not well documented. Metasediments of the Finlayson and Lumby Lake greenstone belts, within the Wabigoon Subprovince, are the focus of this study (Fig. 1). Zircon ages from the volcanics and intrusives cutting volcanics constrain the eruptive episode to 2999 Ma and greater than 2936 Ma for the Lumby Lake and Finlayson Belts respectively (Stone et al., 1992), and overlying sediments may be related to this older volcanic episode (Fenwick, 1976). The surrounding Mafic Tonalite and Old Tonalite of the Marmion Lake Batholith and Tonalite Gneiss of the Dashwa Gneiss complex are 3001, 2953 and 2928 Ma, respectively (Davis, in Stone et al., 1992)

Sedimentary facies within the Finlayson belt consist of metaconglomerate, course-pebbly sandstone, medium-grained sandstone, and fine sand and silt turbidite deposits. Lesser chemical sediments include cherty iron formation and sulfide facies iron formation.

The Lumby lake clastic sediments consist of matrix supported conglomerate, fine sand and silt turbidites, and graphitic slates. Chemical sediments, including, ferruginous chert, chert-magnetite IF, chert-siderite IF, sulfide facies IF, and marble, are dominant in the Lumby Lake metasediments.

Well developed lateral and vertical trends are recognized within the Finlayson Lake metasediments. The Little Falls lake area, in the extreme south-west of the belt, is dominated by course-pebbly sandstone, medium sandstone and conglomeratic beds. Traveling north, along strike, finer grained sediments become increasingly more prevalent, with only fine sand-silt turbidity current deposits found in the north-east. Vertical trends are recognized by an increase in average grain size as one moves up section toward the dominant synclinal axes running north-south through the main sedimentary belt of

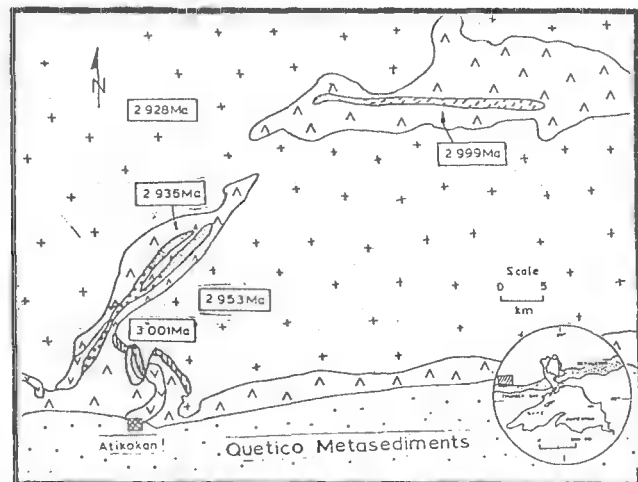


Figure 1 Location of the Finlayson and Lumby Lake greenstone belts. Lithofacies symbols are the same as Figure 2.

Finlayson Lake.

Trends within the Lumby Lake belt are similar. Metasediments grade along strike from dominantly fine sand-silt turbidites with minor chemical sediments, in the west, to predominantly chemical sediments in the east. A progressive change from chemical dominated sediments in the lower section, to clastic dominance in upper sections, is the vertical trend recognized.

Similarities in the sedimentary facies present, and in lateral and vertical trends, suggest that the Finlayson and Lumby Lake metasediments indicates sedimentation within a single basin. The predominance of felsic volcanic clasts within conglomeratic facies may represent subaerial volcanism to the south. It is suggested that clastic sediments were derived from a higher relief source in the south, and prograded through a shallow water environment in the Little Falls and southern Finlayson Lake area. Deeper water turbidity current deposits and chemical sediments are found in the more distal northern Finlayson and Lumby Lake area. Figure 2 represents a possible paleogeographic reconstruction.

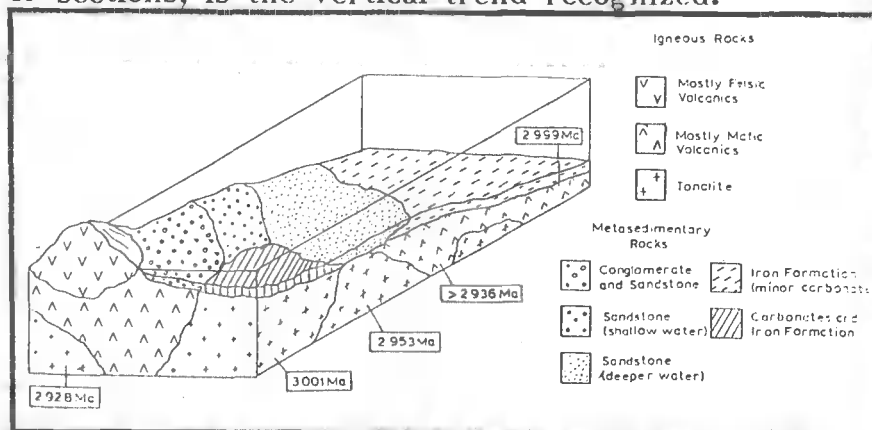


Figure 2 Paleogeographic sketch of the Finlayson and Lumby Lake area. Clastic sediments prograde north, from a volcanic source region, over distal chemical sediments.

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NEOARCHEAN COASTAL SEDIMENTATION IN THE SHEBANDOWAN GROUP, NORTHWESTERN ONTARIO

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Many present day tidal environments, such as the Bay of Fundy and the Dutch Wadden Sea, have been the objects of broad and comprehensive studies. Such environments in the Phanerozoic have also been extensively studied, and as a result, there exists a wealth of information on tidally influenced environments. Although represented in the rock record, very little work has been done on tidal settings in the Precambrian. The majority of studies have concentrated on such environments in South Africa, with little emphasis on Precambrian rocks elsewhere in the world.

In the Canadian Shield of northwestern Ontario, there exists an excellent example of a Precambrian tidal environment. The section containing this example is located approximately 50 kilometres west of Thunder Bay, near Finmark. The rocks, which are Neoarchean in age, belong to the Shebandowan Group and occur within exposures of the Shebandowan - Wawa greenstone belt. A lack of bioturbation has allowed for the superb preservation of sedimentary structures within these units.

A variety of primary sedimentary structures such as herringbone cross-bedding, ladderback ripples and flaser to lenticular bedding are present. These structures are considered characteristic of tidally-influenced environments. Many of the sedimentary structures closely resemble those that are present in Phanerozoic and present-day tidal flat environments. Moving offshore from the tidal flat environment into the subtidal, coarse grained material dominates. Trough cross-stratification and parallel lamination are present. There is no evidence in the sequence that there were lengthy periods of emergence above sea level.

Fining and coarsening trends are present throughout the section. The majority of individual layers fine upwards into silts and muds from a coarse grained sandy base. On a larger scale, the section exhibits an overall coarsening trend when moving towards the subtidal and nearshore environment, or towards the centre of a tidal channel. Occasionally, a fining trend is superimposed upon this overall coarsening trend, such as when moving out of a tidal channel and back into the tidal flat environment.

There are also unique features present in the rocks of this area. For example, 10 to 20 centimetre thick parallel laminated coarse grained sand layers, which grade into thin fine-grained tops are present. The sand layers, which are light in colour, stand in marked contrast to the darker coloured rocks of the section. These layers are believed to represent wave deposition of sand on a beach during a storm, and appear with regularity throughout the section. The presence of storm layers in the tidal flat environment differ from the prevailing thought that storms usually move sediment offshore. The storm layers may be indicative of storms which occurred during periods of high spring tides.

Tidal channels present throughout the section differ from those that are commonly described in the literature. Typically, tidal channels are meandering, but in this case, the tidal channels show very few features that are diagnostic of either meandering or braided channels. Herring-bone cross-stratification and parallel lamination are present in the channels, with sediments fining towards the centre of the channel.

Terwindt (1988) outlined characteristics of supratidal deposits, such as the presence of plant remains, gypsum or salt pans. None of these features are present, in fact the supratidal environment appears to be completely absent. The absence of supratidal deposits is often noted in descriptions of Precambrian tidal settings, and may be a reflection of environmental conditions that were prevalent during this time period

The excellent preservation of sedimentary structures enables the determination of a paleotidal range for this ancient tidal environment. A minimal tidal range of 3.5 metres was calculated, using methods outlined by Klein (1971), and Terwindt (1988). This value is comparable to other determined paleotidal ranges of Precambrian tidal environments, which range from 0.5 to 12.5 metres.

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NEW OBSERVATIONS ON THE GEOLOGY OF THE WESTERN GOGEBIC IRON RANGE, NORTHERN WISCONSIN

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From 1992 to 1994 we reexamined the Gogebic Iron Range between Tyler Forks River and the western termination of the range near Lake Namekagon. Several aspects of the stratigraphy and structure of the range have been revised.

The Bad River Dolomite, at the base of the Early Proterozoic section, attains a maximum thickness of about 300 meters near the Marengo River south of Grand View, Wisconsin. It is typically a dolomitic marble with abundant lenses and beds of chert, partly replaced by tremolite. Farther east, from near Penokee Gap to near Ballou Creek, the Bad River is much thinner and is mostly a monolithic chert breccia and conglomerate, locally with lenses of dolomite near the base. This lithology is interpreted to be a residuum of chert nodules and beds formed as the dolomite was dissolved during the weathering interval prior to deposition of the unconformably overlying Palms Formation. The residuum was variably reworked into conglomerate with clastic quartz grains interspersed in otherwise cherty matrix. Local concentrations of magnetite and hematite, explored in numerous test pits, may be either placers or hydrothermal iron concentrations.

Near Atkins Lake, in the far western part of the range, the Ironwood Iron-Formation grades laterally from typical cherty banded iron-formation into magnetic argillite and non-cherty silicate iron-formation. Large sills of metadiabase are also common in the iron-formation in contrast to the situation in the central part of the range where igneous rocks are rare.

In the Atkins Lake area the iron-formation also contains two interlayers, up to about 10 meters thick, of an unusual breccia consisting of angular slabs of banded siliceous sedimentary rock that are as much as a meter long. Some slabs are bent and may not have been fully lithified when incorporated in the breccia. The slabs superficially resemble nearby iron-formation, but with only a few exceptions, we have not observed fragments that are iron rich or magnetic. The matrix is a dark gray-green, mostly massive rock, at least partly of igneous origin. Although metamorphism has obscured much of the original textures, in places a basaltic texture and small euhedral plagioclase phenocrysts are well preserved, as are amygdules. The origin of this rock is controversial, even among the authors. It may be a "pepperite" intruded at shallow level in the iron-formation prior to

lithification. Alternatively, it may be an extrusive that has incorporated sediments over which it flowed. Salient features arguing for an extrusive origin are: 1) perfectly concordant contacts with thinly laminated iron-formation well exposed at several outcrops, and the lack of any observed cross-cutting contacts, 2) the exotic nature of virtually all fragments in the breccia and the absence of fragments of iron-formation with which the breccia is interlayered, and 3) marked lithologic contrast between the breccia and undoubtedly intrusive sills of coarse-grained, massive, inclusion-free metadiabase within the same outcrops.

Regardless of whether the breccias are extrusive or very shallow intrusions, they indicate that abundant igneous activity was occurring contemporaneously with iron-formation deposition in the western part of the Gogebic Iron Range. The situation is similar to that of the eastern part of the range, where the Emperor Volcanic Complex is interlayered with the Ironwood Iron-Formation. Apparently the platform-like conditions of the central part of the range, where volcanic rocks are limited to a few thin ash beds, grade both east and west into more volcanically active regions at both ends of the Gogebic Iron Range.

Although volcanism appears to have been contemporaneous with iron-formation deposition on the Gogebic Iron Range, we have found no Early Proterozoic mafic rocks cutting the overlying Tyler Formation. This observation, coupled with the prominent unconformity at the base of the Copps Formation, the Tyler equivalent on the eastern Gogebic Iron Range, suggests a time gap between iron-formation deposition and accumulation of the overlying graywacke-slate sequence during which volcanic activity ended.

The Penokean structural history of the area has also been clarified. Penokean deformation increases in intensity from the Tyler Forks area, where deformational features are limited to a few outcrop-scale folds, to the Mineral Lake area, where the iron-formation is repeated by large, nearly isoclinal folds. Those folds were originally upright, but because of northward rotation during development of the Midcontinent rift, they are now recumbent, and the south limbs of synclines are overturned.

From the east end of Mount Whittlesey to the west end of the range, Early Proterozoic strata are structurally detached from underlying Archean rocks. The basal decollement is well exposed on the east end of Mount Whittlesey, where Bad River Dolomite lies on a shear zone developed in Archean dacitic breccia. A decollement within the sedimentary section is also well exposed along the Marengo River where an intensely sheared zone several tens of meters wide separates Bad River Dolomite and Palms Formation. Second-order faults splay upward from the decollement, generally climbing higher in the section to the east. On Mount Whittlesey, the Ironwood Iron-Formation is repeated by one of those faults which results in the unusually wide outcrop belt of iron-formation.

**INSTITUTE ON LAKE SUPERIOR GEOLOGY 1995
MINERAL POTENTIAL EVALUATION, CENTRAL MINNESOTA**

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ABSTRACT:

The Minnesota Department of Natural Resources, Minerals Division, has completed a low-cost program using computer enhanced contemporary methods to evaluate the mineral potential of a large part of Central Minnesota Proterozoic greenstone belts. This project is oriented toward identifying nonferrous metallic mineralization, associated alteration or lithologic units and structures permissive of such mineralization. This information will become a part of the Central Minnesota geographic information system. The objectives are: 1. To serve land use planning within the D.N.R.; 2. To encourage private exploration through better data access, and; 3. To serve government agency planning of future programs.

Creating an improved data base for regional mineral potential evaluation was done by: 1. Listing mineral occurrences, and defining lithologic units and structures permissive of mineral deposits. 2. Describing and analyzing bedrock lithologies from existing drill core. 3. Creating 1:62,500 scale inferred geologic maps, which display interpreted mineral potential. 4. Re-evaluating existing geochemical surveys using contemporaneous statistical analytical methods. 5. Testing geophysical interpretations with drill holes.

A contract was completed by Dr. Don L. Shettel Jr. and Dr. Patrick O'Hara to interpret three existing ground water and lake sediment geochemical data sets using computer driven state of the art statistical and geochemical modeling methods. From these models Drs. Shettel and O'Hara constructed anomaly maps for gold, base metals, iron and uranium.

Contracts were also completed by Dr. Allan Spector to make inferred geologic maps of sixty-two contiguous townships at a scale of 1:62,500, using geophysical (primarily aeromagnetic and gravity data), also geologic data. Detailed magnetic ground traverses and geophysical measurements of density and magnetic susceptibility were made on selected logged samples for computer modeling of geologic features based on geophysical data. Dr. Spector's maps display structurally deformed, folded and faulted, greenstones with associated metasedimentary units and intrusives. An important aspect of this contract was construction of maps displaying mineral potential areas as modeled from geophysical characteristics of known mines located in similar Precambrian terrains, based on the contractor's experience with such features. Several areas of mineral potential are coincident or partially coincident with anomalous geochemical results defined by Drs. Shettel and O'Hara. In the Shephard Area these Mineral Potential Areas include MPA2a, MPA5c and MPA6b; In the Shephard Area Extension they include areas A3, A4 and A10. On the Camp Ripley map there are Mineral Potential Areas, MPA3 and MPA4, close to drill holes with anomalous gold and platinum group elements, Section 12, T43N, R32W.

In summary significant results include: Improved definition of geologic features; Lithologic units and features permissive of economic ore deposits; Detailed inferred geologic maps with definition of areas having mineral potential; Multi-element geochemical anomalies with significant pathfinder element anomalies coincident with favorable inferred geologic features. To test the inferred geology, in cooperation with the Minnesota Geological Survey, six vertical holes were drilled through glacial overburden to obtain bedrock samples. Examination of the core confirms inferred geologic bedrock map lithologies in most of the drill holes. Native copper in a Keweenaw like conglomerate from hole P295-6 suggests mineral potential. Minnesota DNR Report 284 records 960 ppb gold in a heavy minerals concentrate for sample 23949. This sample came from a gravel pit in Section 36, T44N, R31W, near the trend of a mafic volcanic-sediment contact where Spector maps several mineral potential areas on the Shephard Area.

GENESIS OF CU-NI SULFIDE MINERALIZATION AT THE SPRUCE ROAD DEPOSIT, SOUTH KAWISHIWI INTRUSION, DULUTH COMPLEX

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The South Kawishiwi intrusion is one of several intrusions within the Duluth Complex, Minnesota - the principal exposed plutonic component of the 1.1 Ga Midcontinent Rift system. In the Spruce Road area the South Kawishiwi intrusion is divisible into seven distinct troctolitic to gabbroic units, four of which contain 1 to 5 volume percent of disseminated pyrrhotite, cubanite, chalcopyrite, and pentlandite. $\delta^{34}\text{S}$ values of the mineralized units range from 3.8 to 10.2‰, and are distinctly different from those of non-mineralized rocks which range from -3.4 to 2.8‰ (Figure 1). The proposed model for the genesis of the sulfides involves the mixing of sulfur derived from two sources, accumulation of immiscible sulfide liquid, and emplacement of sulfide-saturated magmas. Twenty percent batch partial melting of a spinel lherzolite mantle source with ~20 ppm Cu and 200 ppm S yields a derivative melt with ~76 ppm Cu (65 ppm from sulfide and 11 ppm from silicate) and a total sulfur content of ~1000 ppm. In order to produce the relatively evolved, high-Al olivine tholeiite parental magmas of the intrusive sequence, extensive fractional crystallization of a primary melt in a lower crustal or mantle chamber is required. During this process sulfide saturation would have been achieved and chalcophile elements removed from the magma into a coexisting sulfide liquid. Emplacement of the sulfide-saturated melt into a higher level staging chamber permitted the assimilation of sulfur from metasedimentary country rocks. Reaction between externally-derived sulfur and metals initially present in the melt as silicate, oxide, or neutral species, would have produced a second generation of immiscible sulfide liquid that mixed with that of mantle origin. Sulfide-rich rocks of the South Kawishiwi intrusion represent melts derived from the high-level chamber that had experienced contamination with sulfur of crustal origin. Because of the wide range in possible contaminant $\delta^{34}\text{S}$ values (e.g. 0 to 29‰ in sulfides from metasedimentary country rocks), it is difficult to accurately assess the proportion of country rock sulfur present in the mineralized units, but a range of from 30 to 70% is consistent with available data. Sulfide assemblages are mineralogically zoned, such that pyrrhotite-rich layers are overlain by cubanite-chalcopyrite-rich layers. *In situ* crystallization, controlled by boundary layer fractionation and upward expulsion of Cu- and Ni-enriched residual liquid is proposed to explain the zonation. Upward increases in Cu and Ni contents, as well as incompatible elements such as Zr, Y, and P, may be controlled either by a filter-pressing mechanism, or possibly as a result of the decrease in density of an interstitial liquid related to enrichment of volatiles.

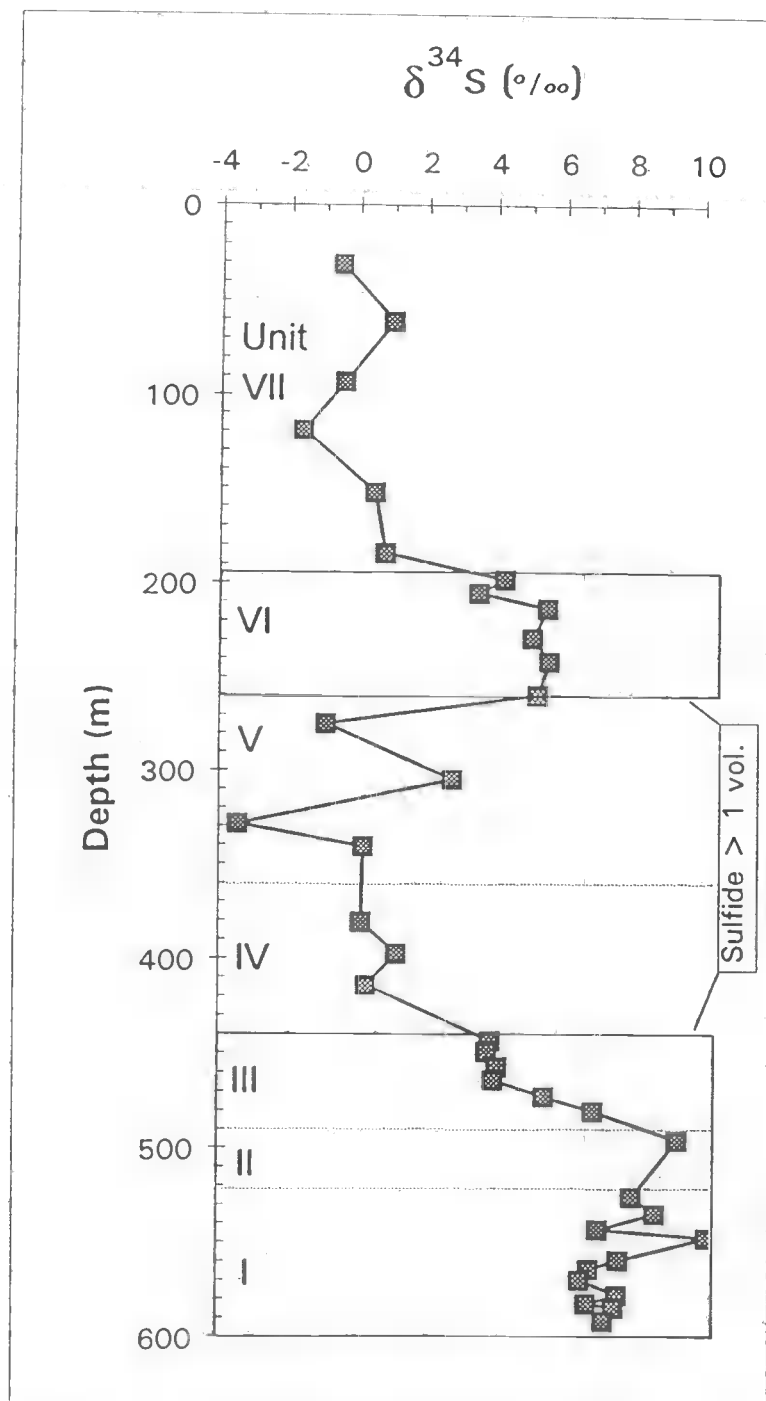


Figure 1. $\delta^{34}\text{S}$ values of sulfide minerals in the South Kawishiwi intrusion, Spruce Road area, Duluth Complex, MN.

Geochemical relationships between the Sublayer, Main Mass, and Offsets, Sudbury Igneous Complex, Canada

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Analyses of the major element oxide and trace element concentrations in samples from the Main Mass felsic norite, quartz gabbro, and granophyre of the Sudbury Igneous Complex (SIC) confirm that there is a compositional gap between norites (e.g. 55-60 wt.% SiO₂, 3.5-5.5 wt.% MgO, 5-8 ppm Th, and 5-10 ppm Nb) and granophyres (e.g. 65-74 wt.% SiO₂, 0.5-1.6 wt.% MgO 13-17 ppm Th, and 12-18ppm Nb). Despite the differences in elemental concentrations, there is a remarkably narrow range of ratios of the rare earth elements (REE), Ba, Rb, Th, U, Nb, Ta, Hf, Zr, and Y in the felsic norite and the overlying granophyre (e.g. La/Sm = 5.4-7.0, Gd/Yb = 2.1-2.6, Th/Nb = 0.9-1.1). These similarities in ratios of elements are unlikely to be explained if the granophyre and felsic norite crystallised from magmas derived from different sources; rather, these data support models where the felsic norite and granophyre are derived from a common magma. We explore the implications for this data for the formation of the Main Mass of the SIC, and suggest that the observed variations are inconsistent with in-situ crystallisation of a single intrusion or melt sheet. The reason for this is suggested to be the compositional gap between the felsic norite and the granophyre which is not readily explained by fractional crystallisation of one pulse of magma.

The composition of quartz diorite from the Parkin and Whistle Offsets and leucocratic norites from the embayment structure at Whistle Mine, at the north-eastern margin of the SIC occupy tight similar fields (quartz diorite: 55-64wt.% SiO₂; leucocratic norite: 59-62 wt.% SiO₂). The ratios of the REE and other incompatible trace elements for these rocks are very similar to those of the Main Mass (e.g. Th/Nb = 0.8-1.2, La/Sm = 5.3-6.6; Gd/Yb = 2.3-3.0), although in detail, when these samples are normalised to average felsic norite, they are slightly enriched in the light REE. Comparison of the data for the Parkin Offset to other offsets around the SIC suggest that there is a broad compositional difference between those formed north of the SIC compared with those formed to the south. With the exception of the Manchester Offset, those formed to the south have TiO₂ = 0.65-0.80 wt.%, Sr = 150-350 ppm, La/Sm = 5-6 and La/Yb = 10-15, whereas those formed to the north have TiO₂ = 0.8-1.1, Sr = 350-550 ppm, La/Sm = 5.8-6.8, and La/Yb = 16-23. The Manchester Offset has low TiO₂ and Sr with elevated SiO₂, La/Sm, and La/Yb. Although the trace element ratios of most of the Offsets overlap with the Main Mass of the SIC, the small differences between those to the north and south of the SIC may be consistent with contamination by compositionally different country rocks.

Our new data for the Sublayer at Whistle Mine suggest that there is a compositional spectrum between orthopyroxene-poor norites through norites containing up to 40 modal percent cumulate orthopyroxene; the more orthopyroxene-rich samples sometimes contain fresh Fo₆₅₋₆₇ olivine. The portion of the embayment closest to the Whistle Offset contains leucocratic norite and quartz diorite. We believe that the classification of either the quartz diorites of the Offsets or the leucocratic norite of the embayment as Sublayer-type rocks may be inappropriate, and we suggest that they are more closely related to the magma giving rise to the Main Mass of the SIC.

Compositional data for the noritic matrix of the Sublayer in the embayment structure at Whistle Mine indicate that the bulk composition of the Sublayer is more mafic (45-53

wt.% SiO_2 ; 5-12 wt.% MgO) than the felsic norite and heterogeneous with respect to major and trace element abundance. Much of the heterogeneity may be due to the variable amount of assimilation of diabase and gabbro inclusions. The composition of inclusion-free Sublayer norite is markedly different when compared to average felsic norite of the Main Mass. The Sublayer from the Whistle embayment has $\text{Ti/Y} = 175$, $\text{Dy/Hf} = 1.4$, $\text{La/Sm} = 3.9$, and $\text{La/Ta} = 105$, which contrasts with the felsic norite which has $\text{Ti/Y} = 220$, $\text{Dy/Hf} = 0.9$, $\text{La/Sm} = 6.2$, and $\text{La/Ta} = 61$. Compositionally, the diabase and gabbro inclusions have $\text{Ti/Y} = 192$, $\text{Dy/Hf} = 2.8$, $\text{La/Sm} = 3.2$, and $\text{La/Ta} = 44$. It is shown that the composition of the Sublayer matrix reflects a component of assimilation of hornfelsed diabase inclusions, and the composition of the Sublayer is inconsistent with the assimilation of large amounts of footwall granitoid. The compositional difference between the Sublayer norite and the Main Mass norite suggests that they were emplaced as different batches of magma, one of which was laden with partially assimilated inclusions of diabase. The presence of inclusions of Sublayer norite in the massive sulphides and footwall breccias suggest that the breccias and sulphides were formed after at least some of the Sublayer magma had crystallised. In detail, a more complete understanding of the geochemical variations in the Sublayer will come from detailed microprobe studies of the accessory mineral phases such as apatite, zircon, baddeleyite, and biotite.

Geochemical variations within the Sublayer and the mafic-ultramafic inclusions, Whistle Mine, Sudbury Igneous Complex, Canada

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The Sublayer norites in the embayment structure at Whistle Mine, Sudbury Igneous Complex (SIC) consist of orthopyroxene-poor to cumulate orthopyroxene-rich non-poikilitic textured norites with up to 5 modal percent sulphide and 10% inclusions. The Sublayer norite often contains inclusions and tends to be heterogeneous; multiple samples from the same outcrop showing 1-10 times more variation than is attributed to analytical uncertainty. The inclusion-free norites are less heterogeneous, mostly with 1-5 times more variation than can be attributed to analytical uncertainty. A small number of samples of Sublayer norite contain fresh olivine of composition Fo₆₅₋₆₇ with 970-1310ppm Ni.

The inclusion population at Whistle is equally split between hornfelsed diabase-gabbro inclusions with anhedral porphyritic clusters of feldspar, and poikilitic-textured melanorites and pyroxenites. It is shown that compositional data for the diabase-gabbro inclusions indicate broad similarities in major and trace element composition to Matachewan diabase dykes. The melanorite inclusions contain cumulate magnetite, apatite, zircon, baddelyite, orthopyroxene, $\pm$ olivine, and intercumulus augite, plagioclase, biotite, and sulphide. They are fresh rocks and are unusual in having very high apatite (0.3 modal %), and biotite (5-10 modal %) contents, olivine with Fo₇₂₋₇₄ and 1270-1490 ppm Ni, yet whole-rock MgO contents of 15-22 wt. % MgO and 50-80 times chondrite LREE abundances.

The melanorite and pyroxenite inclusions range in composition from 8 to 28 wt. % MgO; the least mafic poikilitic-textured melanorites have trace element abundances and ratios which, on average, are similar to the Sublayer norite matrix. The olivine-bearing melanorite inclusions and pyroxenites have elevated Ti/Y, Dy/Hf, La/Ta, and low La/Sm which are all features of the Sublayer matrix, but the most ultramafic samples show strong depletion in the HREE compared to the Sublayer matrix. Nd isotopic analysis of the melanorites indicate that ϵ Nd (1.85Ga) is between -6 and -7 which compares with the Sublayer matrix which has ϵ Nd (1.85Ga) of between -7.5 to -8.

There is a significant range in trace element abundance and ratios in the melanorites and pyroxenites, and in detail, much of this appears not to be linked to any single fractionating mineral phases such as olivine or hypersthene. Rather, we suspect that the compositional variations are more a function of variations in the modal accessory mineralogy of the rocks, and we therefore suggest that mineralogical studies represent an important next-step in unravelling the origin of the Sublayer.

In the course of our studies, we have acquired compositional data from a number of embayment structures around the SIC, and we find that each embayment contains noritic Sublayer matrix with a distinctive trace element signature. For example, analysis of Sublayer matrix from the Fraser and McCreedy Mine areas on the northern margin of the SIC more closely resembles the composition of the main mass norite; at Crean Hill Mine at the southwestern margin of the SIC, the trace element signature has marked low Ti/Y accompanied by low La/Ta which is different to both the Whistle embayment and the Fraser-McCreedy embayments. These differences between embayments suggest contributions from differing crustal reservoirs, and suggest that the Sublayer magmas

equilibrated at depth and *in-situ* with either different conduit walls and/or different inclusion populations.

BANQUET TALK - ABSTRACT

The relationship between mantle plumes, flood basalts and mineralization

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A remarkable wealth of information on the chemostratigraphy of the basaltic rocks found in large igneous provinces is now available. Studies of continental flood basalt (CFB) sequences of the Karoo, Parana, Deccan, Keweenawan, West and East Greenland, and Siberian Traps indicate that 1-15km thick successions of basaltic rocks can be erupted close to continental margins onto young epicontinental sedimentary sequences and ancient amphibolitic to granulitic terrains. These giant CFB record the eruption of large volumes (up to $2 \times 10^6 \text{ km}^3$) of magma over in some cases very short time intervals (e.g. Deccan Trap: $< 1 \text{ Ma.}$). Single lava flows may extend for several hundred kilometers laterally, and the chemical stratigraphy of the lavas can be matched over these distances, and the basalts can be grouped into Formations.

An important issue concerns the relationship of these CFB to mantle plumes or hot spots. In oceanic settings, mantle plumes are believed to control the distribution of ocean island chains such as the Hawaiian chain. Some of these island chains converge with CFB at continental margins, and the Reunion-Chagos-Lacadeive system is one example where the age of the rocks becomes progressively older away from the present-day Reunion Island hot spot towards the 60 Ma. Deccan Trap. In detail, recent work has shown that even the eruptive centers within the Deccan appear to have migrated from north to south as the Indian Subcontinent migrated northwards over the Reunion hot spot.

In other settings, eruption of CFB appears more directly related to passive rifting of continental margins. An example of this is the more protracted (c. 30 Ma.) Parana CFB. In detail however, both the Parana and Etendeka fall close to the pre-rifting location of the Tristan de Cunha hot spot, and so even in these cases plumes appear to have played a role.

These features are all very satisfying confirmations of the effects of continental migration over mantle plumes, but the really exciting implications of these data come from their application in mineral exploration strategies. One of the largest deposits of magmatic Ni, Cu, and platinum group elements is associated with the Noril'sk Region of the Siberian Trap. Other major deposits are associated with the Keweenawan, and extensive exploration programs have been pursued around the Insizwa Complex of the Karoo and the Greenland CFBs.

At Noril'sk in the Siberian Trap, the lavas are split into two sequences. The Lower Sequence has high TiO_2 (> 1.7) and Gd/Yb (> 2) relative to the Upper Sequence, but both sequences contain picritic basalts. The Lower Sequence appears to have been derived from deep asthenospheric mantle as the geochemical composition of the least contaminated rocks closely resembles ocean island basalt remobilised from the mantle by a hot spot. The Upper Sequence consists of a few picritic flows overlain by tholeiites, and these rocks have geochemical signatures suggesting derivation from a combination of shallow asthenospheric mantle and the continental mantle lithosphere. Basalts from the lower part of the Upper Sequence have high SiO_2 , LILE, LREE, and elevated Th/Nb , La/Sm , and radiogenic Sr-isotopic compositions. Basalts with 52-56wt.% SiO_2 , $\text{La/Sm} > 3$, and Sr-isotope signatures greater than 0.707 have interacted with upper continental crust, and become contaminated. Importantly, these lavas are also long bereft of their Ni, Cu, and PGE, and have $\text{Cu/Zr} < 0.2$ and $\text{Ni/MgO} < 10$; these are features attributed to the equilibration of the magma with a sulphide liquid. Upwards in the basalt stratigraphy, the degree of contamination recorded in the rocks is progressively less and this couples with

an increase in the tenor of Ni, Cu, and PGE. These features are found in the Nadezhdinsky Formation lavas, and these lavas were erupted in the Noril'sk Region close to the Noril'sk-Kharaelakh Fault. The amount of Ni, Cu, and PGE missing from the Nadezhdinsky Formation lavas is more than enough to account for the mineralisation at Noril'sk and Talnakh. The Noril'sk and Talnakh intrusions consist of at most several hundred meters of picritic to gabbroic rocks, yet host thick lenses of massive Ni-Cu-PGE mineralisation. The importance of the basalts in this context is that their low Ni, Cu, and PGE contents are presumably due to the extraction of the metals by the same sulphide that is found at Noril'sk; the compositions of the basalts then become important exploration tools. In detail, the combination of the elemental and isotopic composition of Sr in the intrusions and lavas, together with the S-isotopic composition of the sulphides suggest that much of the sulphur in the Talnakh ores was derived from Devonian evaporites. This suggests that evaporite sulphur played a very important part in the genesis of the Noril'sk deposits.

In the Keweenawan, a thick sequence of lavas on the Black Bay Peninsula and St. Ignace Island (the Osler Group) record many of the same features as the Noril'sk basalts. The Lower Formation of the Osler Group have many similarities to the Lower Sequence at Noril'sk and may be linked to a mantle plume that initiated rifting. The Central Formation of the Osler Group has elevated SiO_2 , La/Sm, and Th/Nb, and these same lavas have very low Ni/MgO and moderate to low Cu like the Nadezhdinsky basalts of Noril'sk. Unfortunately Cu was mobile during alteration, and therefore this criterion is less diagnostic than the Ni/MgO ratio. The presence of abundant gabbroic rocks along the northern margin of Lake Superior and in the Nipigon Plate, combined with the presence of giant Ni-Cu deposits at Duluth and smaller deposits in the Crystal Lake Gabbro and Port Coldwell Complex encourage further exploration for Noril'sk-type targets in the Keweenawan.

STRUCTURAL GEOLOGY AND TECTONIC EVOLUTION OF THE VIZIEN GREENSTONE BELT IN MINTO BLOCK, NORTHEASTERN SUPERIOR PROVINCE, NORTHERN QUEBEC

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The Minto Block in the northeastern Superior Province is characterized by north-northwesterly structural and aeromagnetic trends that contrast with easterly to east-southeasterly trends in the southern part of the province. It consists mainly of plutonic rocks, but also contains some greenstone belts with well-preserved supracrustal sequences, including the Vizien, Kogaluc, Payne Lake and Qalluviartuuq belts. During our study of the Minto Block, we paid special attention to the greenstone belts, because they generally contain a more complete structural record than associated granitoid rocks. Here we report results of a detailed structural study of one of the belts, the Vizien belt, and discuss their tectonic implications.

The Vizien belt consists of five structural panels (A, B, C, D and X). Panel X consists of pillowed, nonvesicular, low-K tholeiitic basaltic andesites intruded by peridotite and gabbro sills (~2786 Ma), and is interpreted to be a fragment of transitional oceanic crust. Panel A consists of upward-shoaling calc-alkalic (submarine to shallow-marine or subaerial) mafic, intermediate and felsic volcanic rocks (~2724 Ma) and minor sedimentary rocks, and is interpreted to have formed in a continental arc environment. Panel C consists of a bimodal sequence of subaerial high-K tholeiitic lava flows of ~2722 Ma, interpreted to have formed in a continental extensional environment. Panel B consists of a basal conglomerate (<~2718 Ma) and greywacke that lie unconformably on saprolitic tonalitic basement of ~2940 Ma. The top of panel B consists of enigmatic mafic tholeiitic lavas and a melange that is in shear zone contact with, and contains clasts of, panel X. Panel D consists of highly strained rocks of panels B, C and X.

Detailed structural analysis of the Vizien belt demonstrates five generations of ductile deformation (D1 to D5), as well as brittle faulting. D1 is indicated by the presence of a pre-D2 foliation and deformed melange fragments. It is interpreted to be related to the thrusting of panel X over B. D2 is responsible for the main penetrative foliation (S2), axial-planar to tight to isoclinal F2 folds. The S2 foliation generally strikes subparallel to the panel boundaries and lithological contacts, and dips steeply. On the S2 foliation, steeply plunging mineral and/or stretching lineations are well developed. The D2 deformation is concentrated in a shear zone between panels X and A/C. Kinematic indicators indicate that panel X was thrust over both panels A and C during D2. F3 and F4 folds are open to tight, with NNW-SSE- and E-W-trending axial planes, respectively. In contrast to the F2 folds, they lack an axial planar foliation. F3 and F4 folds warp the S2 foliation, panel boundaries and lithological units. They dominate the map pattern. D5 is associated with dextral transcurrent movement along a NNW-SSE trending shear zone.

Analysis of the structural data indicates that the S2 foliation was planar before being folded by F3. Therefore, the pre-F3 geometry of the belt can be restored by reorienting S2 into a planar geometry. The restored geometry of the Vizien belt is much simpler, with panel B on one side, and panels A and C on the other side, of panel X. This regular geometry suggests that panels A and C were probably part of the same block when they were juxtaposed with panels B/X. Similar La/Nb ratios and Nd isotope compositions in panels A and C support a model in which panel C formed in a rift within the panel A continental arc. The arc was separated from the basement of panel B by oceanic crust, anomalous fragments of which may be preserved as panel X. The collision related to the closure of the ocean was responsible for the D1 deformation, during which panel X was thrust over panel B. Deposition of panel B sedimentary rocks is tentatively interpreted to have occurred in a foreland basin; geochronological data on panel B volcanics will resolve whether they are autochthonous or exotic. D2 deformation was related to back-thrusting, during which panels X/B were overturned and thrust over panels A/C.

PREDICTION AND DISCOVERY OF PGE OCCURENCES IN THE DULUTH COMPLEX AT DULUTH

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Two intervals of anomalous PGE concentrations have recently been discovered in the medial part of the layered series of the Duluth Complex at Duluth. These discoveries, though far from economic, validate earlier speculation (Miller, 1993) that Cu-Ni sulfide and PGE mineralization might be associated with abrupt changes in cumulate mineralogy and texture that are thought to represent interruptions to the steady-state crystallization of the magma.

The layered series at Duluth (DLS) is a 4-km-thick mafic layered intrusion that was emplaced in the lower part of the North Shore Volcanic Group (NSVG). Preceding the emplacement of the DLS was the formation of an approximately 1-km-thick accumulation of gabbroic anorthositic rocks of the anorthositic series. Despite a sharp chilled contact between the DLS and the overlying anorthositic series, the two series have identical U-Pb ages of 1099 ± 0.5 Ma (Paces and Miller, 1993). Overall, the internal structure of the sheet-like DLS dips $25-40^\circ$ to the east, roughly conformable with the enclosing volcanic rocks.

The cumulate stratigraphy and cryptic layering of the DLS is consistent with bottom-up fractional crystallization of a shallow (4-8 km) tholeiitic magma body that was intermittently open to recharge and eruption. The DLS can be divided into 5 stratigraphic zones (Miller and others, 1993). Above a 200- to 300-m-thick, heterogeneous **basal contact zone** of coarse-grained olivine gabbro and medium-grained troctolite, the DLS passes into to a 1- to 1.5-km-thick **troctolite zone** of mostly homogeneous troctolitic (Pl+Ol) cumulates. Marked by an abrupt transition to a coarse ophitic olivine gabbro at its base, a 1-km-thick **cyclic zone** is characterized by at least five, 50- to 200-m-thick, macrolayered couplets of troctolitic and gabbroic (Pl+Aug+Ox±Ol) cumulates. Typically abrupt reversals to troctolitic cumulates mark the base of the next cycle. The gabbroic cumulate intervals locally contain cm- to m-scale layers and lenses of fine-grained ilmenitic olivine gabbro (microgabbro), which are closely associated with the PGE mineralization. The cyclic zone gives way to a 1- to 1.2-km-thick **gabbro zone** that is composed mostly of iron-rich gabbroic cumulates with locally abundant anorthositic series inclusions. The **upper contact zone** is defined by a loss of cumulate texture and is very uneven in thickness owing to the irregular nature of the contact with overlying anorthositic series. The zone is composed of a hybrid range of rock types from apatitic quartz ferromonzodiorite, which makes up most of the zone where it is thickest, to biotitic ilmenite ferrodiorite, which everywhere forms the "chill" against the anorthositic series.

Many models of sulfide-hosted PGE mineralization in mafic layered intrusions (e.g., Campbell and others, 1983; Boudreau and McCallum, 1992) stress the importance of disruptions to the steady-state fractional crystallization by such processes as magma recharge, country rock assimilation, volatile fluxing, and eruption. With recent mapping and petrologic studies (Miller and others, 1993) indicating such an openness to the DLS system, the Minnesota Geological Survey, with funding from the Minerals Coordinating Committee of the Minnesota State Legislature, has set out to evaluate its potential for base- and precious-metal mineralization. A particular target for study was the macrolayering of the cyclic zone. At intermediate stages of fractional crystallization and under low-pressure conditions (1-2 kb), the DLS magma was saturated in olivine and plagioclase and was evidently nearing saturation in gabbroic phases of augite and ilmenite. Although the transitions from troctolitic to gabbroic cumulates within the cyclic zone may have formed from normal crystallization differentiation causing saturation in these phases, the abruptness of the transitions and the lack of noticeable cryptic variation across the units suggest that abrupt changes in physical conditions of crystallization also may have played a role. Such a change may have been an increase in pressure resulting from volatile (CO_2 and perhaps H_2O) saturation of the magma in the roof zone. The build up of volatiles in the roof zone is consistent with the pervasive hydrothermal alteration of the anorthositic series and could have caused failure of the cupola leading to volcanic eruption and decompression of the chamber. Evidence of such decompression is suggested by the similar ferrodioritic composition and fine-grained texture of the microgabbro layers within the gabbroic cumulates of the cyclic zone and of the "chill" against the anorthositic cap. Because of the strong positive effect of pressure on water solubility in mafic magma at low total pressures, decompression may result in water-saturated conditions which has the effect of dramatically raising the solidus temperature of the magma and thereby quenching it. Such a process could have caused simultaneous rapid crystallization of

the DLS "chill" zone and microgabbro layers. Water-saturated conditions are indicated by the common occurrence of biotite phenocrysts in the DLS "chill". A decompression-quench origin for the DLS "chill", as opposed to a thermal quench, better explains the similar age of the DLS and anorthositic series and the composition of the "chill", which is too evolved to be parental to the entire DLS. The return to troctolitic cumulate crystallization may have resulted from recharge and reinflation of the magma chamber by new magma or may simply indicate a return to lithostatic pressures following cessation of volcanic eruption.

Decompression also appears to have a negative effect on sulfide solubility in silicate magmas, at least at low pressures (Poulson and Ohmoto, 1990). Evidence that a sulfide segregation event accompanied decompression quenching is given by the discovery of an anomalous concentration of sulfide (0.5 wt %) at the base of a microgabbro layer. Moreover, the concentration of sulfide (0.10-0.07 wt %) in the upper "chill" zone is in the range expected for sulfide saturation of an iron-rich (>10 wt %) melt at low pressure (Poulson and Ohmoto, 1990). Finally, the observation that the average sulfide concentration in cumulates below the cyclic zone is about 0.02 wt %, compared to about 0.06% in the upper part of the intrusion, is consistent with the magma becoming sulfide saturated at the time of cyclic zone formation. Sulfide saturation by decompression would cause segregation of a dense sulfide melt throughout much of the magma system that could then scavenge the magma of PGE as it settled to the floor of the chamber. The first occurrence of sulfide melt to form in this way should produce the highest concentration of PGE.

Recognizing the potential for Cu-Ni sulfide and PGE mineralization to be associated with horizons representing perturbations to the steady-state crystallization of the DLS, a suite of 50 hand samples were selected for whole rock and Pt-Pd-Au assay analysis. As predicted by the model outlined above, anomalous PGE concentrations were found associated with abrupt changes in rock type in the cyclic zone. The two most PGE-rich samples are situated at similar interfaces between gabbroic cumulate and microgabbro and at approximately the same stratigraphic level within the second macrocyclic unit of the cyclic zone. The most anomalous sample has 444 ppb Pt, 443 ppb Pd, 56 ppb Au, whereas the other has 44 ppb Pt, 108 ppb Pd, and 56 ppb Au. The two samples differ greatly in their Cu-Ni sulfide concentration with the high PGE sample containing 0.028% S, 163 ppm Cu, and 568 ppm Ni and the lower PGE sample containing 0.50% S, 5392 ppm Cu, and 852 ppm Ni. Average PGE concentrations for the other 48 samples are approximately 10 ppb Pd, 7 ppb Pt, and 4 ppb Au.

Follow-up studies are in progress to confirm and more fully characterize the extent and nature of this PGE mineralization. Nevertheless, the importance of this discovery is that it was predicated on detailed characterization of the igneous stratigraphy of the DLS and petrologic interpretations of that stratigraphy. Similar detailed studies along the northwestern margin of the Duluth Complex (Severson and Hauck, 1990; Severson, 1994) reinforce the contention that such an approach is the most effective means of evaluating the mineral potential of layered intrusions.

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**Kimberlite heavy mineral indicators in overburden, Michipicoten
River- Wawa Area, Northeastern Ontario.**

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Two diamonds, and possibly a third, were recovered from the Wawa area by C. Clement (local prospector) during the summer of 1991. The exact location of the discovery site cannot be positively identified. It is thought, however, that the diamonds were collected from either older alluvium (sand and gravel) in a point bar of the Dead River, near the Michipicoten River and/or modern alluvium (sand and gravel) associated with Wawa Creek. The diamond discovery was reported to the Ontario Geological Survey (OGS) in the fall of 1993.

Two of the 3 diamonds were loaned to the OGS and then forwarded to the Royal Ontario Museum, Department of Mineralogy, for confirmation. The stones were identified as industrial grade diamonds with carat weights of 1.05 and 1.13.

A sampling program was initiated by the OGS in September of 1993, in order to establish authenticity of the diamond find. Ten, 25 kg samples were collected from the reported discovery sites: 5 modern alluvium samples from Wawa Creek and 5 older alluvium samples from a point bar associated with the Dead River.

Kimberlite indicator minerals (KIM's) isolated from these samples include one "G10" garnet with a kelyphite rim, and 9 chrome diopsides. Most of these indicators were recovered from the Dead River point bar and verified that the 2 industrial grade diamonds could have been recovered from this site.

As a follow-up to these preliminary discoveries, the OGS undertook a regional sampling program in the Michipicoten River- Wawa area in the summer of 1994. The area was considered optimal for kimberlite exploration as: a) it includes the area where the 2 diamonds and associated heavy minerals were recovered; b) bedrock and overburden geology is well understood (Morris 1990, 1991, 1992a, 1992b; Sage 1994); and c) the area is close to the Kapuskasing structural zone, an area thought to be a favourable kimberlite host (Boland and Ellis 1989).

Methodology, results and recommendations for kimberlite exploration from the 1994 summer field program are presented in Morris et al. (1994). Kimberlite indicators identified from the Michipicoten River- Wawa area include: a) 4 "G10" chrome pyrope garnets and 37 "G9" chrome pyrope garnets; b) 4 high chrome chromites and 104 low chrome chromites; c) 121 magnesium rich ilmenites; and d) 39 chrome diopsides.

Several areas were identified as favourable for kimberlite exploration from: a) the distribution of total KIM's; b) evaluating site results e.g. the presence or absence of significant KIM's ("G10's and high chrome chromites); and c) the variety of KIM's. All of the favourable areas exist on, or southeast of, the northern margin of the Kapuskasing structural zone.

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Heavy mineral indicators, Wawa Area

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THE CURRENT SETTING OF THE HEMLO GOLD DEPOSIT, ONTARIO: IMPORTANCE OF FUNDAMENTAL RELATIONSHIPS

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The deformed Hemlo Gold Deposit (HGD) occurs within moderately to strongly strained, folded, transposed, and metamorphosed volcano-sedimentary rocks of the Hemlo-Schreiber greenstone belt. Lithologic interpretation in this part of the belt is impeded by polyphase strain, possibly polyphase metamorphism, and locally extensive, complex hydrothermal events. Many of the interrelationships among these events are not well constrained. Strain superposed on the HGD is of one, and likely 2, generations. Metamorphism has affected the deposit in 1 (medium grade) or more events. The deposit appears to predate felsic plutonism, which predates a D₃ dextral shear event.

The HGD is neither stratiform nor strata bound. Much of the deposit currently:

- occurs on the hanging wall side of the south limb of a large-scale, S-shaped fold, delineated, in part, by massive and fragmental, felsic, quartz-plagioclase-phyric rocks;
- lies largely within 2 or more, closely spaced, 290°-striking high-strain zones, that occur within the most pervasive, highly strained part of an otherwise westerly striking belt; and
- transgresses transposed units such that it is hosted largely by highly altered sedimentary rocks in the east and central parts, and by altered sedimentary rocks and quartz-plagioclase-phyric rocks in the west part.

Ore-grade mineralization and at least some types of alteration are presently structurally controlled at various scales. Notable changes in alteration and mineralization occur from one part of the deposit to another, particularly spatially associated with an inflection in the greenstone belt, from W-striking to WNW-striking. There is an extensive envelope of altered rocks in the west end of the deposit and a narrow alteration envelope towards the east end. Strain, metamorphism, and alteration superposed on the HGD have modified various aspects of the primary alteration and mineralization characteristics, which has resulted in additional alteration of country rocks, and remobilization of Au, Mo, Hg, As, and Ba.

Various depositional models have been applied to the HGD. Establishing fundamental field relationships is of paramount importance for evaluating the appropriateness of a given model. Particular attention must be given to:

- identifying protoliths and establishing contact relationships, both of which are critical to some depositional models;
- determining which generations of structural elements predate, postdate, or are synchronous with the deposit;
- distinguishing features resulting from regional metamorphic events as opposed to hydrothermal alteration events, and putting into context their relative timing with respect to structural elements; and
- characterizing what current features of the deposit reflect modification by events subsequent to emplacement.

Other sites within the Hemlo--Schreiber greenstone belt, which contain barite and display alteration similar to that of the HGD, may reflect large-scale, synchronous or diachronous hydrothermal events.

KEWEENAWAN UPLIFT AND SUPERGENE OXIDATION OF PRE-PENOKEAN, SUPERIOR-TYPE IRON FORMATION

Jon North

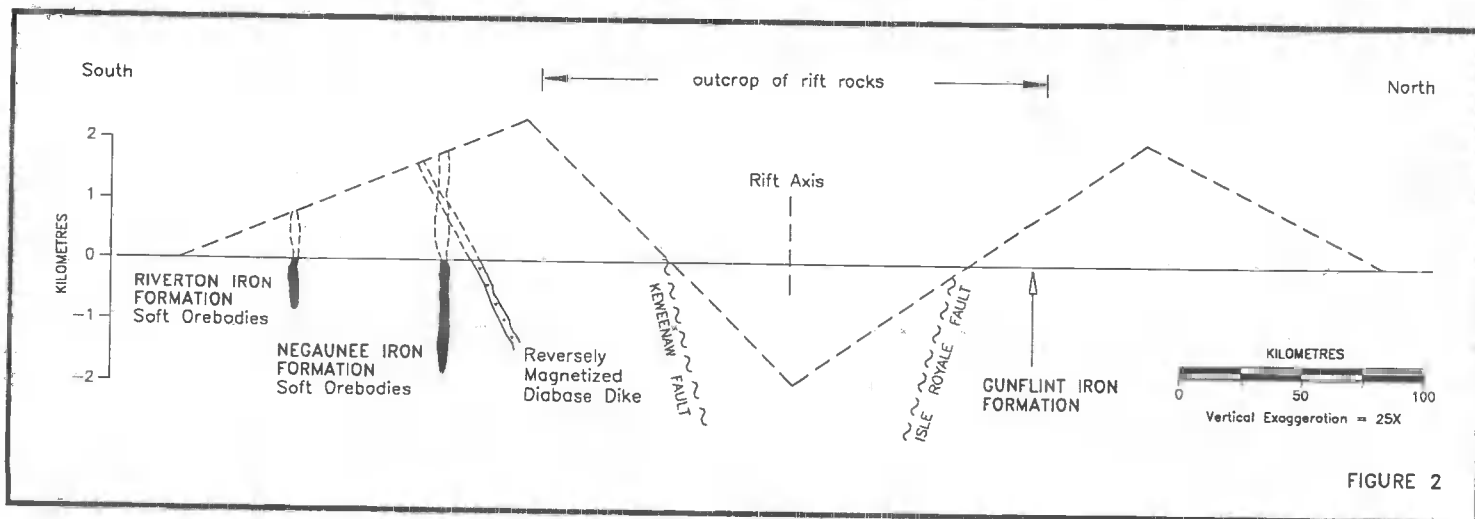
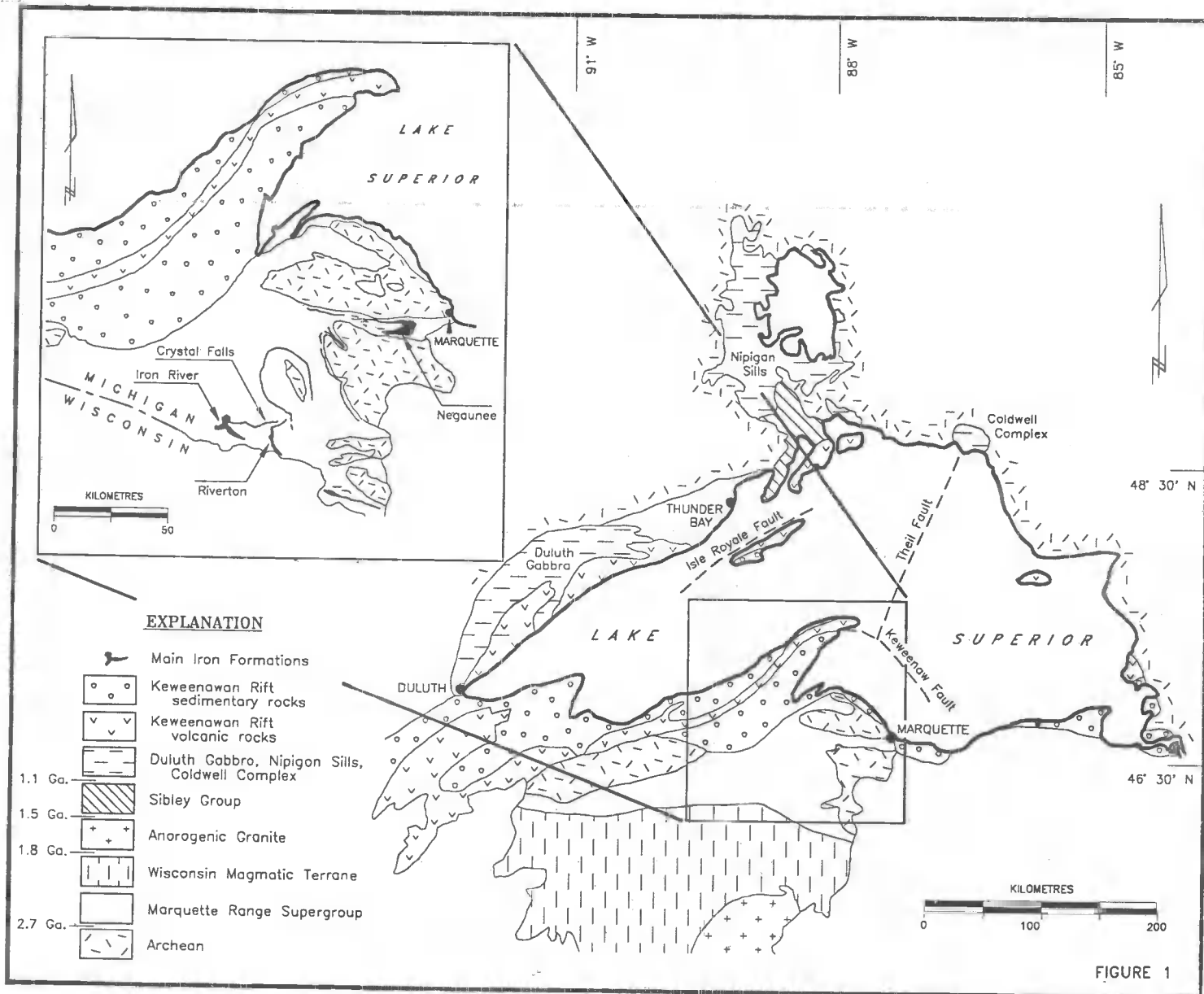
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The Riverton and Negaunee Iron Formations are lower Proterozoic Superior-Type Iron Formation respectively within the Paint River and Menominee Groups, Marquette Range Supergroup, Michigan (Figure 1). The primary iron formation is carbonate or oxide facies and contains 20 to 30% iron. The Marquette Range Supergroup was deformed and metamorphosed during the ca. 1.85 Ga Penocean orogeny and subsequently intruded and overlain by rocks of the Keweenawan Rift at ca. 1.1 Ga. Stratabound bodies of secondary, massive hematite-goethite containing greater than 50% iron were mined as high grade direct shipping "soft" iron ores. The orebodies occupy axes of plunging synclines or other upward-opening structures in contact with footwall aquicludes, they are not deformed, and of lower metamorphic grade than their host rocks. Soft iron ore is at maximum depths of 800 m in the Riverton Iron Formation and 1800 m in the Negaunee Iron Formation.

Formation of soft iron ore is a two stage process of i) widespread pseudomorphism of siderite by hematite and goethite and ii) dissolution of chert and replacement by hematite and goethite. Mn is fractionated from iron and depleted in iron ore relative to primary iron formation. The isotopes of oxygen in iron oxide minerals imply that the iron oxides interacted with waters with variable $\delta^{18}\text{O}_{\text{SMOW}}$ of -6.85 to 16.69 per mil. Present meteoric waters at the latitude of the Paint River Group are ca. -10 per mil.

Hence, the soft iron ores probably formed by the interaction of meteoric water with primary iron formation but not present meteoric water. Because Mn and Fe can be dissolved in waters of low pH but ferric oxides or hydroxides precipitate at high Eh whereas manganous ions can be transported at high Eh, the fractionation of Mn from Fe in the iron ores implies that they formed at low pH and high Eh as in acidic supergene weathering profiles.

The soft iron ores most likely formed when the water table was lowered because of uplift of the Marquette Range Supergroup on the south ridge and flank of the Keweenawan Rift at about 1.1 Ga and, meteoric water descended through the iron formations, along a footwall aquiclude to the static water table. Hence they represent supergene oxidation of primary chert-siderite iron formation analogous to karstification with an iron oxide residue. The differential maximum depths of the oxidation of the iron formations to soft iron ores is evidence of differential uplift of the rift flanks across a profile resembling a fedora hat (Figure 2).



Targeting Massive Sulfide Deposit Exploration in the Western Vermilion District: Volcanological Controls

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The last ten years has been a period of rapid growth in the understanding of the formation of volcanogenic massive sulfide deposits. Numerous detailed studies in established mining camps (Noranda, Flin Flon, Sturgeon Lake, etc.) provides data that allows deposit characteristics and volcanic facies changes to be observed and correlated. These studies have made it possible to:

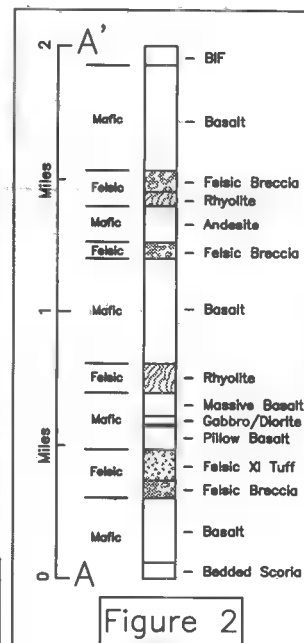
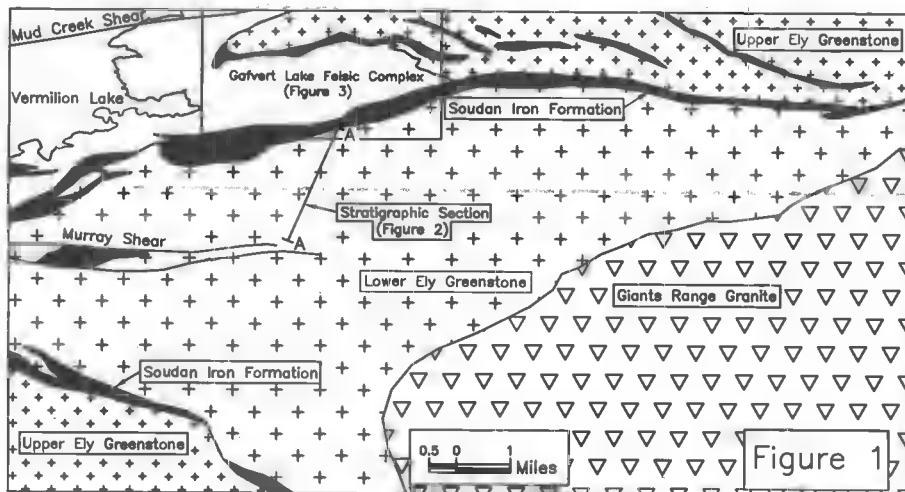
- 1) Describe characteristics and facies of volcanic rocks,
- 2) Discuss methods of deposition and eruption,
- 3) Describe mineralogy and zoning patterns of alteration,
- 4) Describe the significance of synvolcanic intrusions,
- 5) Discuss depositional environments of massive sulfide deposits.

In the western Vermilion District (Figure 1), volcanic reconstruction is the key to targeting favorable volcanic successions for massive sulfide deposit exploration. Detailed mapping by the author over the last two years indicates two areas have favorable volcanic characteristics for hosting such deposits. These areas include: 1) The uppermost two-mile section of the Lower Ely Greenstone (LEG), and 2) The informally named Gafvert Lake Felsic Complex.

Previous mapping in the Lower Ely Greenstone indicated that the formation is composed of roughly 99% massive and pillowed basalt. Recent mapping (1:1,250 to 1:10,000) in the Fivemile Lake area (Figure 2) of the LEG documented many classic features associated with massive sulfide deposits. These features include:

- 1) Regional, semi-conformable alteration,
- 2) Cross-cutting, base-metal bearing chlorite alteration pipes,
- 3) Four mafic-felsic volcanic cycles (the two mile section is 30% felsic breccias, lavas, and tuffs),
- 4) Synvolcanic faults with associated debris flow deposits.

The informally named Gafvert Lake Felsic Complex (Figure 3) is a north facing, composite dacitic volcanic complex overlying the Soudan Iron Formation. The complex is cored by large masses of quartz-feldspar porphyry and blocky dacitic lava flows. Course blocky pyroclastic flow deposits grade outward and interdigitate with fine-grained dacitic tuffs and epiclastic rocks. Thick sill-like masses of quartz-feldspar porphyry occur throughout the complex. The complex is capped by a large mass of carbonate facies iron formation that grades outward into oxide facies iron formation. Lenses of massive pyrite occur directly above the complex within basalts of the Upper Ely Greenstone. The Gafvert Lake Felsic Complex has many volcanic features analagous with Kuroko Type Massive Sulfide deposits.



Gafvert Lake Felsic Complex

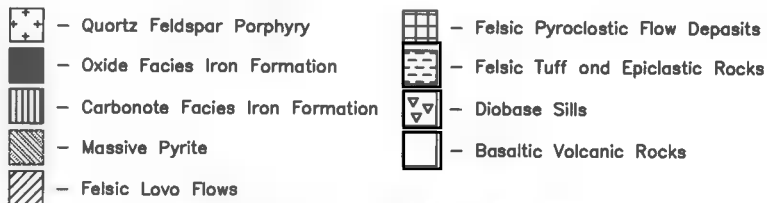
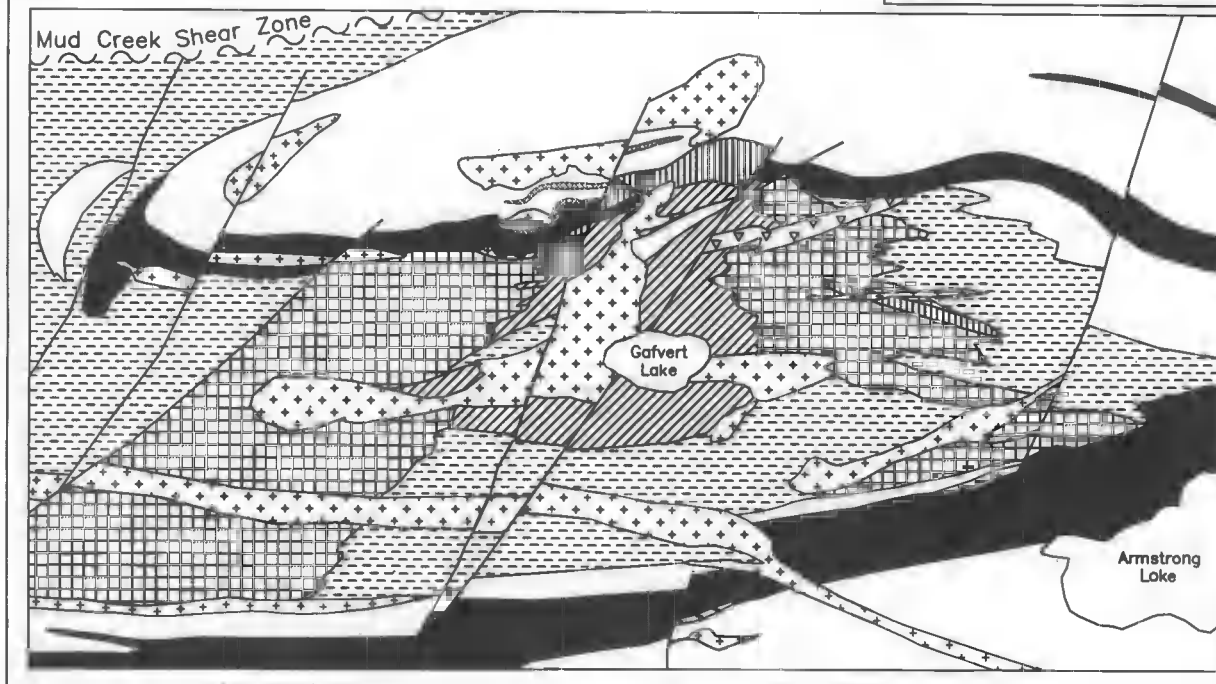


Figure 3



Geological, Geophysical and Geochemical Compilation of the Western Vermilion District: Targeting for Gold and Massive Sulfide Deposits

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Mineral exploration for gold and massive sulfide deposits in the Western Vermilion District has occurred sporadically since the late 1960's. No minable deposits have been discovered, however, these efforts have greatly increased the understanding of the geological characteristics of the district. A digital compilation of all available geological and geochemical data has been integrated into a mineral potential interpretation of the District. The data includes 7573 assays from 2097 outcrop samples and 176 drill holes, integrated geology from the authors mapping, terminated lease files, thesis maps, and government maps. Contoured aeromagnetic data for the area is part of the state-wide 1/4 mile spaced Aeromagnetic Program of the Minnesota Geological Survey.

Over the last thirty years, 145 holes have been drilled for gold in the western Vermilion District. Gold mineralization discovered to date is concentrated within three structurally controlled domains. These domains include:

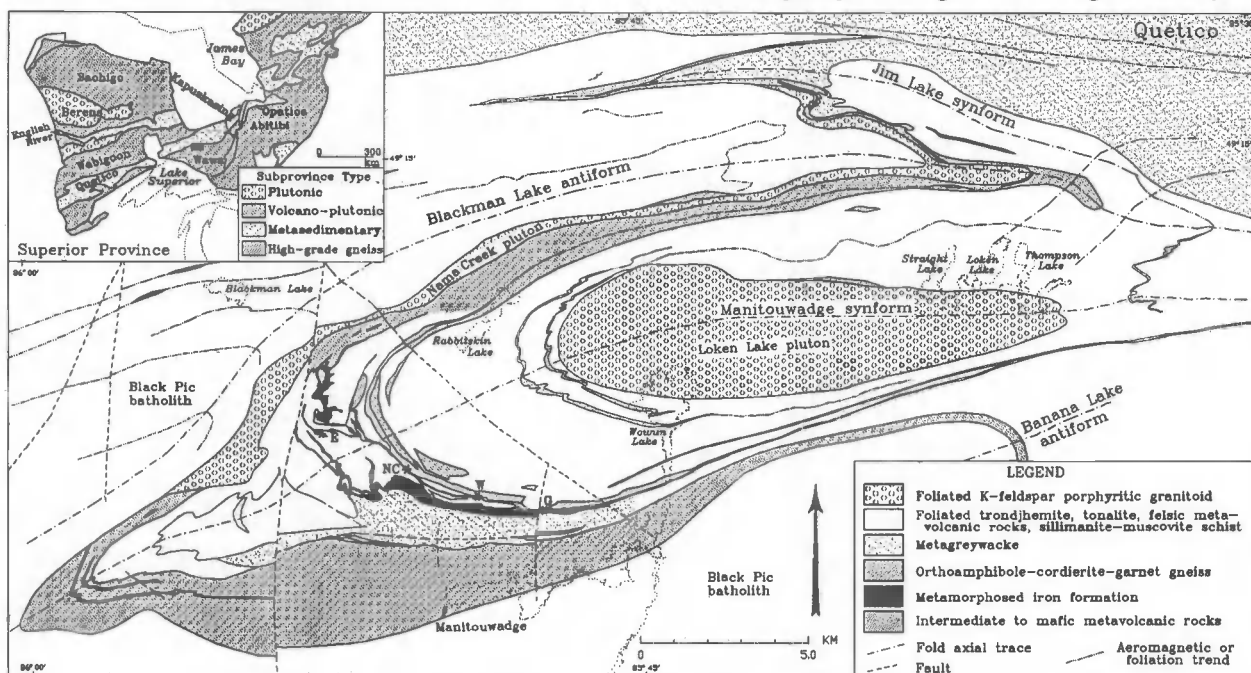
- 1) The wedge shaped block between the Vermilion Fault and the Mud Creek Shear Zone. Mineralization generally occurs at the brecciated contacts of iron formations and quartz-feldspar porphyry bodies. Gold is concentrated in the breccia zones with quartz-pyrite-arsenopyrite matrix.
- 2) The wedge shaped block between the Shagawa Lake Deformation Zone and Burntside Lake Fault.
- 3) Within sheared and carbonatized basalt and porphyries along the Murray Shear zone

Exploration for massive sulfide deposits has generally been targeted upon geophysical anomalies (EM conductors and magnetic highs) within the Upper Ely Greenstone and Soudan Iron Formations. The vast majority of this work occurred during the late 1960's and early 1970's. Recent mapping by the author indicates that large, well exposed areas of the western Vermilion District have yet to be explored for massive sulfide deposits. These areas include the Gafvert Lake Felsic Complex and the Lower Ely Greenstone Formation.

STRUCTURAL EVOLUTION AND AGE RELATIONSHIPS OF THE MANITOUWADGE GREENSTONE BELT AND WAWA-QUETICO SUBPROVINCE, SOUTHWESTERN SUPERIOR PROVINCE, ONTARIO

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Our preferred structural model for the Manitouwadge greenstone belt (northern Wawa subprovince), and the adjacent Quetico subprovince involves four phases of ductile deformation (Figure). The greenstone belt comprises a 2720 Ma mafic-to-felsic volcanic sequence, repeated across an easterly-trending D2 syncline with a central core of metagreywacke. Interlayered metamorphosed felsic volcanic rocks, iron formation and altered rocks in the volcanic sequence north of the D2 syncline are host to volcanogenic Cu-Zn deposits. D1 ductile faults and folds, interpreted from detailed mapping in the area of known base-metal deposits, repeat mineralized horizons. D3/D4 shortening and progressive dextral transpression produced the distinctive synformal structure of the Manitouwadge belt, reoriented D1 and D2 structures, and involved Quetico metasedimentary rocks in map-scale folds. The timing of structural events and accompanying amphibolite-facies metamorphism is partly constrained by the results of an ongoing U-Pb geochronological study.



Geology and location map of the Manitouwadge greenstone belt. G=Geco mine, W=Willroy mine, NC=Nama Creek mine, E=Willecho mine.

D1 faults (shear zones) are recognized from the coincidence of truncated lithological units, repeated mineralized sequences, and zones of straight gneiss interpreted as annealed mylonite. In addition to zones of straight gneiss, D1 planar fabrics are preserved locally in the hinge regions of D2 folds. Although no sense of kinematics or offset has been observed, sequence repetitions, geometries consistent with low angle truncation, and the early relative age of these structures is suggestive of thrusting.

D2 structures include the dominant planar and linear fabrics and many of the outcrop-scale folds, locally with sheath geometry. D2 fabrics are typically defined by high grade metamorphic minerals, suggesting deformation broadly synchronous with peak metamorphism. Among D2 map-scale folds, a sheath fold repeats a major D1 fault and the mineralized sequence in the hinge region of the D3 Manitouwadge synform. D2 shortening resulted in repetition of the volcanic sequence across the easterly trending syncline on the southern limb of the Manitouwadge synform. Metagreywacke in the core of the syncline is folded and contains D2 fabrics. D2 shortening might also account

for the presence of volcanic rocks in the Dead Lake (central to the Manitouwadge synform) and Banana-Otter areas (east of Thompson Lake). Older phases of the Black Pic batholith enclosing the Manitouwadge belt, and K-feldspar porphyritic intrusions, have D2 fabrics and were interpreted as pre- to syn-D2 intrusions.

D3 map-scale folds, including the Manitouwadge synform, Blackman Lake antiform, and Jim Lake synform, fold the Manitouwadge belt and the Wawa-Quetico subprovince boundary. The supracrustal sequence is thickest in the hinge of the Manitouwadge synform, which plunges northeasterly at 25°. D3 fabrics include map- and outcrop-scale folds and a moderately to poorly developed axial planar cleavage. Relationships between metamorphic minerals, migmatitic segregations, and deformation fabrics indicate that D3 was broadly coeval with peak metamorphism in the Quetico subprovince. Map-scale D4 structures modify the geometry of the D3 folds. Examples are the Nama Creek shear zone along the northwest limb of the Manitouwadge synform and open folds in the Wawa-Quetico boundary and the axial traces of the Blackman Lake antiform and Jim Lake synform. In addition, the Banana Lake antiform may have formed by folding and shearing during D3/D4 deformation. Outcrop-scale D4 structures include local kink folds and crenulation cleavage, for example, outcrop-scale asymmetric folds and associated crenulation cleavage in the area of the Geco mine. The dominantly Z-asymmetry of D3/D4 folds, and dextral D3/D4 kinematic indicators, are interpreted as a response to progressive dextral transpression.

Zircon provenance ages constrain the maximum depositional age of Manitouwadge metagreywacke to 2693 Ma (Zaleski et al., 1995), at least 25 Ma younger than 2720 Ma felsic volcanism (Zaleski et al., 1994; Davis et al., 1994). Field observations are equivocal regarding the relationship of D1 deformation and sedimentation; however, uplift resulting from D1 deformation may have contributed sediment sources. Thus, D1 is tentatively constrained to the interval 2720–2693 Ma. U-Pb zircon ages, determined for three pre- to syn-D2 plutons gave 2680 ± 2 Ma and 2687 ± 3 Ma for the Nama Creek and Loken Lake K-feldspar porphyries respectively, and $2687 \pm 3/-2$ Ma for the oldest diorite of the Black Pic batholith. Hence, D2 deformation and peak metamorphism in the Manitouwadge belt are younger than 2680 Ma. A foliated (D2?/D3?) monzodiorite phase of the Black Pic batholith has an age of 2677 ± 3 Ma, within error of the maximum age limit on D2 deformation. Based on the involvement of the Manitouwadge metagreywacke in D2 folds, the age of sedimentation is bracketed by 2693 and 2680 Ma. Given the similarity in lithology and age, we interpret the Manitouwadge metagreywacke as a tectonic outlier of the Quetico subprovince.

Monazites from intrusive and altered volcanic rocks in the Manitouwadge belt give metamorphic and post-metamorphic U-Pb ages of 2669–2676 Ma, and 2661 Ma (Schandl et al., 1991; Davis et al., 1994; Zaleski et al., 1995). U-Pb isotopic analyses of titanite from five intrusive rocks give two distinct age groupings of circa 2673 and 2655 Ma. The 2680 Ma Nama Creek pluton and the 2677 Ma Black Pic monzodiorite have titanite ages of 2672 ± 2 and 2674 ± 2 Ma, respectively, which we tentatively interpret as the time of regional cooling through the 600°C closure temperature of titanite (Heaman and Parrish, 1991). Titanite from the 2687 Ma Loken Lake pluton has an age of about 2652 Ma, and titanite from pre- to syn-D3 dykes gives $2658 \pm 4/-2$ and 2655 ± 3 Ma, suggesting a widespread retrograde hydrothermal event that locally crystallized or reset titanite.

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PALEOGEOGRAPHIC RECONSTRUCTION OF THE GUNFLINT-MESABI-CUYUNA DEPOSITIONAL SYSTEM: A BASIN ANALYSIS APPROACH

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The depositional system responsible for the genesis of the Proterozoic banded iron formations in Minnesota and Ontario has been hotly debated since the mid 1950's. Recent exploratory drilling, the acquisition of high-resolution aeromagnetic data and a better understanding of the regional stratigraphy of the Biwabik and Trommald iron formations in Minnesota during the 1980's has provided insight into the style of deformation that affected the iron bearing strata during the Penokean Orogeny, 1860 m.y. ago. Researchers have since speculated, based on this data, that the deposition of the chemical and clastic sediments which comprise the Animikie Group in Minnesota occurred in a migrating peripheral foreland basin (Southwick and Morey, 1991). This model poses several problems that have yet to be resolved. Most troubling, the model is incapable of explaining the observed lateral distribution of facies in iron formation and associated strata. There is an apparent lack of coarse turbiditic, deltaic and fluvial sediments adjacent to the fold-thrust belt. Also, if iron formation deposition occurred in a migrating foreland, sedimentation would have been restricted to the outer platform (Hoffman, 1987) and consequently the chemical sediments would only be represented by facies characteristic of the distal shelf. The observed lateral distribution of facies within correlatable units of iron formation are to the contrary, a complete shelf sequence, not just the distal portion is present. These inconsistencies have lead to the need for the re-examination of iron formation in Ontario and Minnesota. The current study uses a process oriented approach combined with basin analysis to perform a paleogeographic reconstruction of the Gunflint-Mesabi-Cuyuna depositional system.

Twenty drill holes were logged from the Gunflint, Biwabik and Trommald iron formations. Great care was exercised in recording changes in grainsize, bed thickness, and sedimentary structures present within drill core. This procedure provides critical insight as to whether the organization of iron formation facies was process controlled or governed by an allocyclic mechanism such as fluctuating sea level, or both. Intrabasinal correlations between the Gunflint and Mesabi iron ranges were assisted by the presence of a volcanic ash layer, which served as a stratigraphic marker, and by comparison of sea level curves generated from core logs.

Stratigraphic correlations indicate that iron formation facies within the Gunflint-Mesabi-Cuyuna depositional system exhibit a marked fining and thickening of the entire section to the southwest. The Gunflint is dominated by medium to coarse grained cross-stratified chert grainstone beds 5 to 50cm thick with abundant rip ups. Hummocky cross-stratified well sorted fine grained chert beds are interbedded with parallel and wavy bedded magnetite-rich slaty iron formation packages 3 to 10cm thick. Strata within packages are graded and 1 to 3mm thick. Chemical sedimentary facies comprising the Biwabik iron formation of the Mesabi iron range are distinctly finer grained than those in the Gunflint. Fine to medium grained grainstones 3 to 30cm thick dominate, and are interbedded with wavy and parallel laminated magnetite rich slaty iron formation packages, 10 to 30cm thick. Rip ups are present at the base

of many medium grained cross-stratified chert grainstones. The Biwabik iron formation of the Emily district in the northern segment of the Cuyuna range is composed of interbedded fine grained chert grainstones 1 to 10cm thick and parallel and wavy laminated slaty iron formation. Iron formation facies in the Trommald iron formation from the Cuyuna North range are finer still, and are dominated by graded parallel laminated slaty iron formation. Slaty beds range in thickness from 1 to 4mm and resemble DE turbidites. This lateral distribution of chemical sedimentary facies parallels facies transitions observed in modern shelf-to-slope environments.

Examination of vertical facies trends in iron bearing strata reveals the presence of both first order (sea level) and second order (process controlled) depositional cycles. Three first order cycles are present in the Gunflint and Biwabik iron formations; a basal transgressive cycle, a middle regressive cycle, and an upper transgressive cycle. Each extends 60 to 80 meters upwards through the sequence. A pulse of volcanism is preserved in the lower portion of the upper transgressive cycle as a 3m thick ash layer. Its bottom contact is sharp and indicates a rapid and almost instantaneous influx of volcanoclastic material into the depositional system. Its upper contact is gradational in places and represents waning delivery of volcanoclastics to the Animikie Basin. The presence of similar allocyclic trends have been recorded by Morey (1983). However, their relative stratigraphic positions differ significantly from those observed in this study. Superimposed within first order cycles are smaller, coarsening upwards, second order cycles. These previously unrecognized trends in the Gunflint and Mesabi iron ranges span a vertical distance of 5 to 10 meters. They coarsen gradationally from parallel laminated slaty iron formation to medium and coarse-grained, cross-stratified grainstone successions. Their top contact is gradational but sharp into the base of the overlying cycle. Similar sequences present within the iron bearing strata of the Gogebic iron range in Wisconsin have been interpreted as representing offshore bar complexes. Their presence is significant as depositional processes responsible for offshore bar development provide another mechanism for the genesis of interbedded cherty and slaty iron formation.

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PRODUCTS OF ELECTRIC PULSE DISAGGREGATION OF SOME KEWEENAWAN ROCKS.

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A new facility at the University of Minnesota for disaggregating rocks and minerals with high voltage electrical pulses (Weiblen, 1994) is currently being used to obtain mineral separates from Keweenawan rocks of the Duluth Complex, the Copper Harbor Conglomerate and the Nonesuch Formation. Previous research at the Mechanobr Technical Corporation in Saint Petersburg, Russia has demonstrated the efficacy of electric-pulse disaggregation to separate minerals of contrasting dielectric properties along grain boundaries (Rudashevsky and others). The electric-pulse method of comminution preserves the original grain-size distribution of liberated minerals. This phenomenon, which contrasts with the decrease in grain-size in mechanical comminution, facilitates recovery of fine-grained minerals. Careful materials handling of the disaggregated product remains an important aspect of mineral recovery.

Electric-pulse disaggregation of Cu-Ni bearing samples from the INCO, Spruce Road, Test Pit at the base of the Duluth Complex is being conducted as a part of on-going studies of the distribution and petrogenesis of platinum-group minerals (PGM's) and their recovery. To-date, several here-to-for unreported PGM's as well as gold and silver alloys have been recovered. The PGM's include: the platinum-antimony-bismuth alloys sudburyite and froodite, and grains of platinum-silver-selenide. The liberated grains retain delicate surface growth features and have a limited grain-size distribution (0.01 - 0.1 mm). Although samples from the INCO Spruce Road site were extensively studied by a number of investigators in the past, discrete grains of PGM's have not, to our knowledge, been previously reported from this site. The recovery of PGM grains strengthens the view that a significant portion of the ubiquitous above background to ~ 1 ppm assay values for platinum group elements (PGE's) in the Cu-Ni ores of the Duluth Complex are due to discrete PGM grains. Further studies are being directed toward providing previously unobtainable mineralogical and textural data on PGM's that are needed to devise new and efficient methods of metal recovery from Duluth Complex ores.

The mineralogy and textures of the fine-grained phases in the Copper Harbor Conglomerate and the Nonesuch Formation of the White Pine district, Keweenaw Peninsula, Michigan are being studied by one us (Stoynov) as part of a graduate research program. Electric-pulse disaggregation of samples from these rocks has resulted in the recovery of fine-grained (< 0.1 mm) barite crusts, detrital zircon, and native copper grains with delicate surface growth features. Textural and compositional data on these materials are being used to evaluate models of copper mineralization processes in these rocks.

The electric-pulse facility at Minnesota is available to investigators for exploratory research.

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Kimberlite in Ontario

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To evaluate the presence of diamond deposits in Ontario, the Ontario Geological Survey (OGS) initiated an investigation of known kimberlite pipe occurrences within the province. Each pipe will be classified, it's exploration history defined and models will be developed to outline areas where other kimberlite pipes may exist within the province (Sage 1994).

Presently, there are 2 areas within the province where kimberlite has been discovered. These are the Attawapiskat area and the area along the Lake Timiskaming Structural zone (Figure 1). Kimberlite core has been generously donated to the OGS by companies working in these areas.

KWG Resources and Monopros Limited have provided core from the Attawapiskat area. Dan Scholtz (University of Toronto), Falconbridge Ltd., Findore Minerals Inc., Geological Survey of Canada, KWG Resources Inc., Monopros Limited, Portland Firth, Seymour Sears (Consulting Geologist), Strike Minerals Inc. and Sudbury Contact Mines Ltd. provided core from the Lake Timiskaming Structural Zone. Examples of kimberlite core from each of these areas are available for viewing.

In addition to the core, heavy mineral concentrates are also available for viewing. KWG Resources donated chrome diopsides and pyrope garnets from it's C-14 pipe, Lake Timiskaming Structural Zone area. Monopros Limited donated kimberlite core from the Guigues Pipe, Lake Timiskaming Structural Zone and KWG Resources Inc. donated heavy mineral concentrates.

For each area, kimberlite and heavy mineral concentrates available for display are listed in alphabetical order and in no way reflect the level of importance of the contribution.

Two industrial grade alluvial diamonds (1.05 and 1.13 carat weight) were recovered from the Michipicoten River-Wawa area in the summer of 1991. The local prospector (C. Clement) who discovered the diamonds donated them to the Royal Ontario Museum who, in turn, has loaned them to the OGS for display. The story behind the diamonds and follow-up work is summarized by Morris et al. (1994; this volume).

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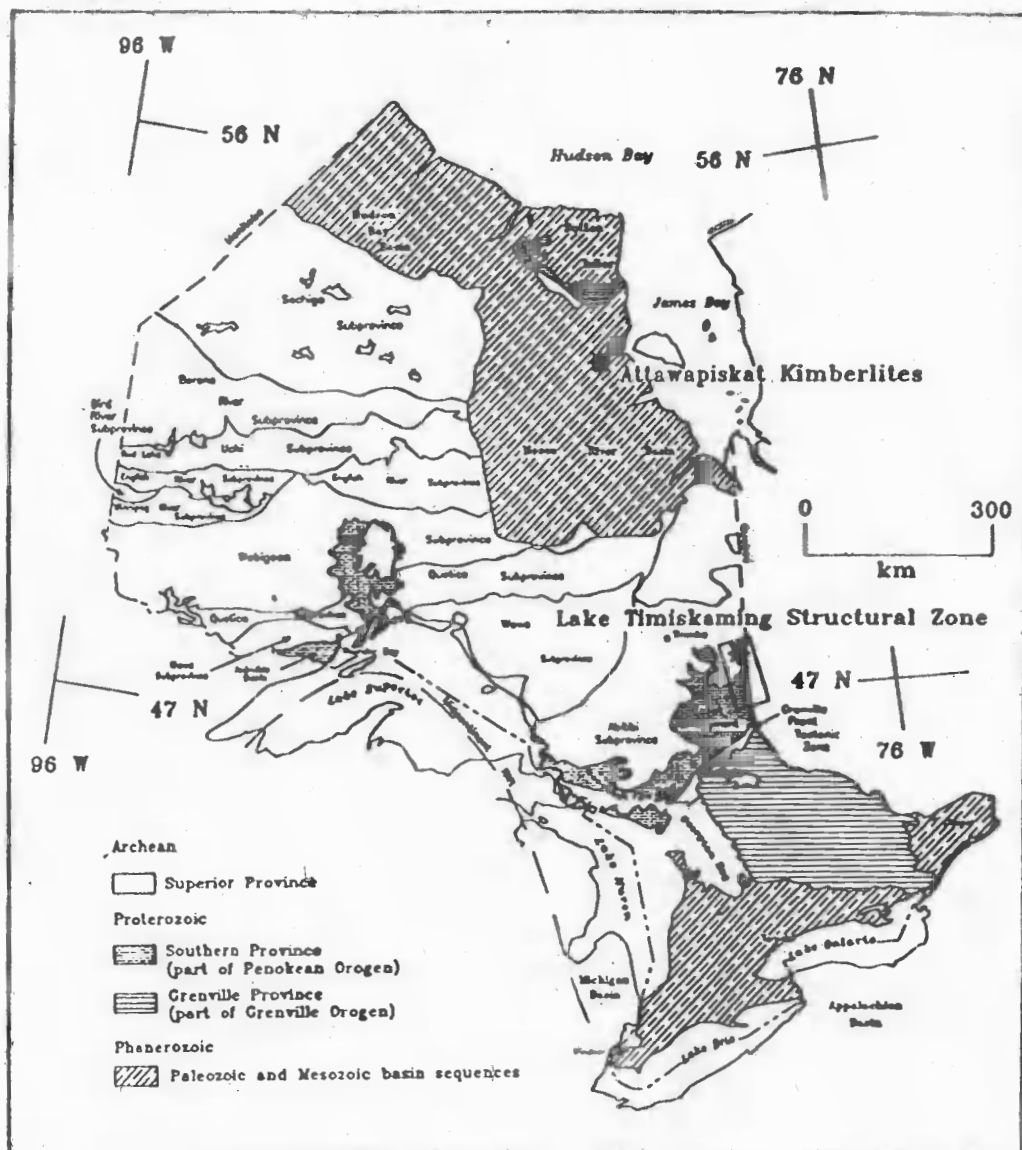


Figure 1. Index map showing the location of known kimberlite clusters in Ontario (from Sage 1994).

COMPARISON OF POST-PENOKEAN THERMAL HISTORIES OF THE WATERSMEET AND REPUBLIC DISTRICTS, NORTHERN MICHIGAN: RESULTS AND IMPLICATIONS OF

$^{40}\text{Ar}/^{39}\text{Ar}$ MINERAL AGE DATING

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In northern Michigan, Archean and Paleoproterozoic rocks were deformed and metamorphosed during the 1870-1830 Ma Penokean orogeny. Attoh and Klasner (1989) determined that rocks of the Watersmeet district reached pressures of 5-6 kbars and temperatures of 500-600°C, whereas rocks of the Republic district attained similar temperatures but much lower pressures (2-3 kbars). This pressure variation across the orogen is consistent with the contrasting ductility in the rocks of these two regions. Paleoproterozoic ductile deformation fabrics are well-developed in nearly all the rocks exposed in the Watersmeet area. In contrast, Paleoproterozoic ductile fabrics are only well-developed in late mafic dike rocks of the Republic district. The contrasting ductility and pressure determinations from these regions suggests they would have experienced different cooling histories following the peak of metamorphism. In order to assess this, we have applied the $^{40}\text{Ar}/^{39}\text{Ar}$ incremental dating method on hornblende and biotite from both regions. These data allow comparison of the thermal histories between the two regions as well as comparison of Ar/Ar biotite ages with Rb/Sr biotite ages obtained previously in other studies.

Results from the Watersmeet district. We dated two hornblende separates from the Watersmeet district. An Archean amphibolite collected within the Watersmeet gneiss dome gave a well-defined plateau age of 1822 ± 18 Ma (total gas age = 1793 ± 12 Ma). We interpret this age as representing simple post-Penokean cooling of these rocks through $\sim 500^\circ\text{C}$ (the closure temperature for hornblende). Hornblende obtained from a mylonitized Archean amphibolite outside the dome gave no plateau age. However, a significant amount of the total gas released gave an age of ~ 1750 Ma, similar to a U/Pb zircon age obtained on a highly sheared Paleoproterozoic rock from within the Watersmeet gneiss dome (Peterman and others, 1986). Both ages probably represent the time of shearing of these rocks at temperatures below $\sim 500^\circ\text{C}$.

We obtained four biotite Ar/Ar plateau ages from rocks within and adjacent to the dome which range from 1760 to 1740 Ma, concordant with the two ~ 1750 Ma Rb/Sr biotite ages obtained by Peterman and others (1980) and Sims and others (1984). One biotite separate from a rock collected 10 km from the dome yielded a somewhat disturbed spectrum with a total gas age of ~ 1700 Ma (oldest increments were 1720 Ma). Our biotite ages are somewhat older than Ar/Ar biotite ages obtained by Winnett (1981) from the same rocks. The discordance between the two studies reflects the difference in the number of increments analyzed per sample together with the fact that low temperature increments are considerably younger than higher temperature increments.

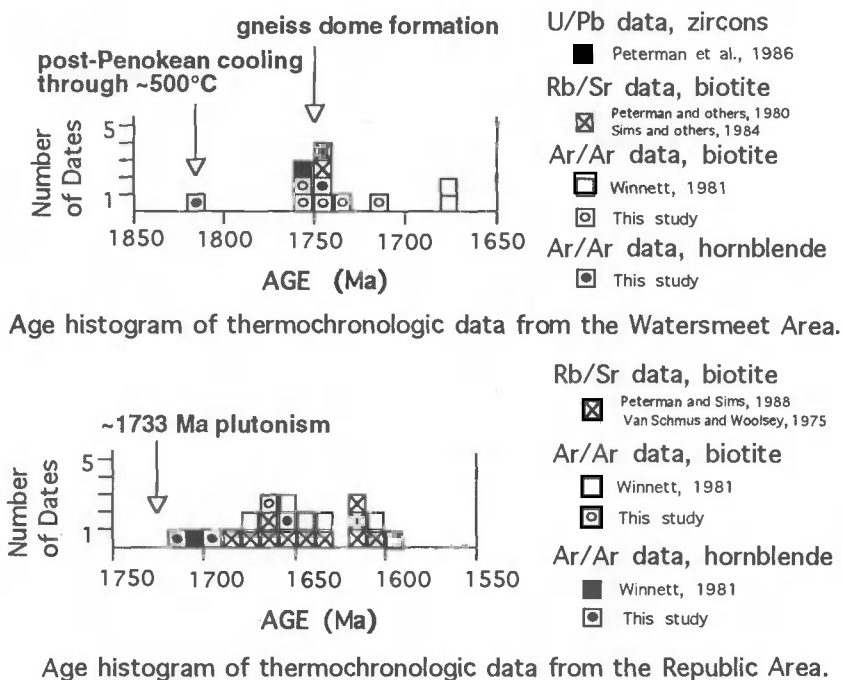
Interpretation. The ages obtained here (see histogram below) support the interpretation of Sims and others (1984) and Peterman and others (1980) that the Watersmeet district experienced significant cooling/uplift and concomitant deformation at ~ 1750 Ma, probably related to gneiss dome formation. However, our 1822 Ma hornblende plateau age indicates that metamorphism in the Watersmeet node is not related to heat transfer associated with rise of the dome rocks. We attribute gneiss dome formation (and deformation of Penokean-aged isograds) to an episode of extensional collapse superimposed on an earlier history of crustal shortening (Schneider and Holm, 1994). Following uplift and stabilization at ~ 1750 Ma, this area has not experienced any significant thermal reheating.

Results from the Republic district. Three hornblende separates were dated from the Republic district, including two amphibolite gneisses of probable Archean age and a Paleoproterozoic mafic dike. One of the gneisses gave a plateau age of 1695 ± 19 Ma and the dike rock gave a slightly older plateau age at 1720 ± 13 Ma. A similar hornblende plateau age (1704 ± 14 Ma) was obtained on a dike rock by Winnett (1981). The third hornblende separate, obtained from a rock collected on the north side of the Marquette syncline north of Republic, did not give a plateau age; it yielded a disturbed spectrum with a total gas age of ~ 1660 Ma. Similar disturbed ages were obtained by Winnett (1981) for rocks collected along the Marquette syncline. While it is difficult to interpret these data, their location along the fault-bounded Marquette syncline suggests their disturbance might be related to reactivation of this zone well after the Penokean orogeny.

Two biotite separates were obtained from two different Paleoproterozoic dikes. One gave an unreasonably old age attributed to excess argon. The other gave a well-defined plateau age of 1678 ± 27 Ma. This age is similar to the oldest biotite ages obtained from this area in previous thermochronologic studies using both the Ar/Ar and Rb/Sr methods (see histogram below).

Interpretation. The hornblende plateau ages obtained from the Republic area are 100 Ma younger than the hornblende age from the Watersmeet area. Given the relatively shallow depth of this region, it is very unlikely that temperatures in the Republic area remained above 500°C until 1720 Ma or so following the Penokean orogeny. We feel that these ages reflect a significant thermal resetting event, strong enough to reset hornblendes, well after the Penokean orogeny. Schulz and others (1988) recently identified a ~ 1733 Ma pluton located northeast of the Republic syncline. This body may be responsible, in part, for the existence of a near surface negative gravity anomaly in the Republic area (Attoh and Klasner, 1989). If so, we speculate that this pluton may also be the heat source responsible for the isotopic resetting. If plutonism at ~ 1730 Ma is not directly responsible for formation of the Republic metamorphic node, it seems at least to be the cause of a major thermal perturbation superimposed on a pre-existing high regional temperature distribution (cf. Peavy metamorphic node; Attoh and Vander Meulen, 1984).

The 1680 Ma Rb/Sr and Ar/Ar biotite ages from the Republic area probably represent the time of cooling through 300°C following the thermal reheating event. The younger scatter in the biotite data is the result of partial resetting associated with the long recognized low-grade metamorphic event at about 1630 Ma.



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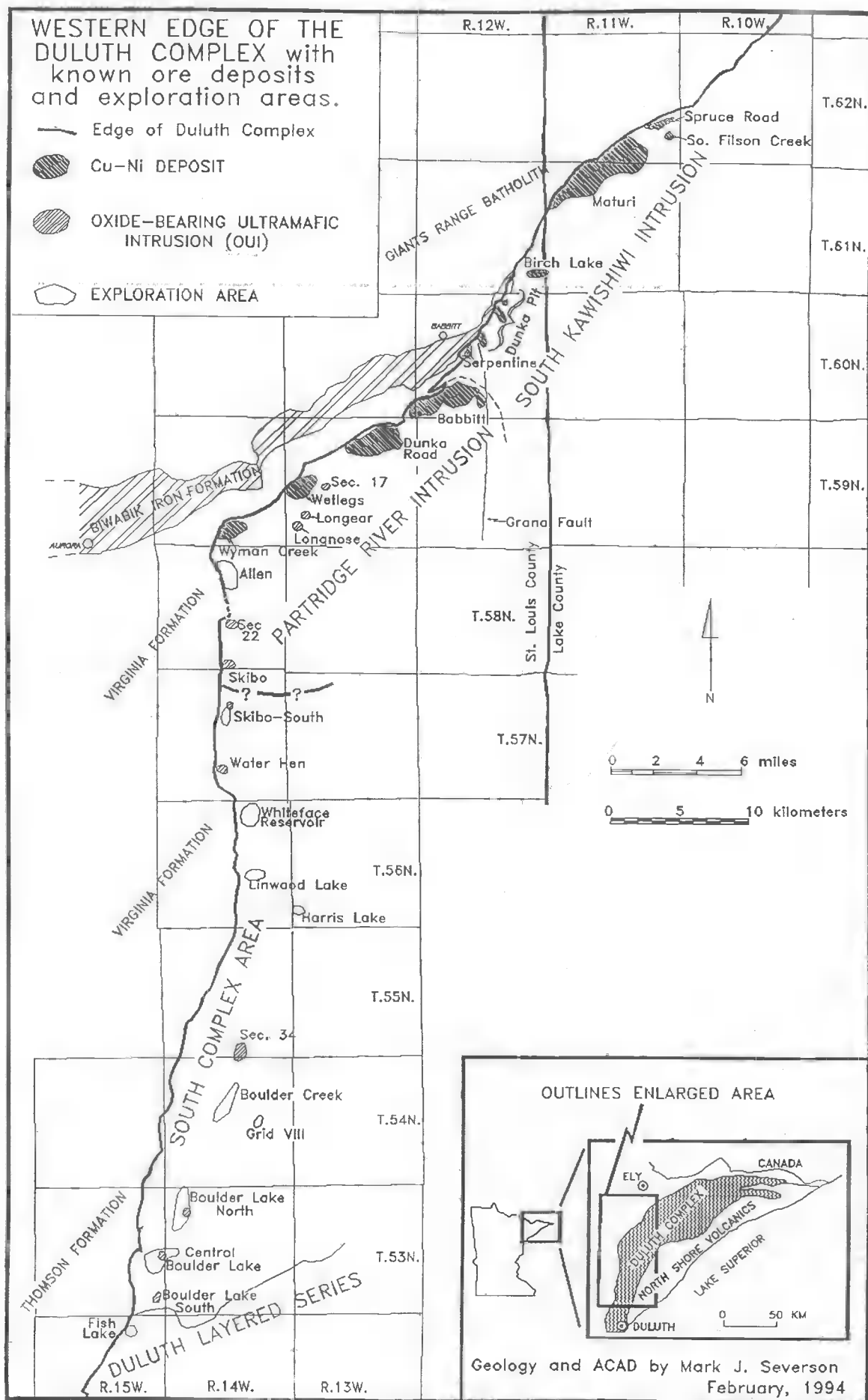
GEOLOGY OF THE SOUTHERN PORTION OF THE DULUTH COMPLEX

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The Duluth Complex (Middle Proterozoic - 1099 Ma) is a large intrusive body that contains numerous smaller intrusions that collectively comprise the Complex. Recent work has shown that igneous stratigraphic sections can be delineated within these intrusions through detailed relogging of drill core, e.g., for the Partridge River intrusion and South Kawishiwi intrusion. More than 140 drill holes are located in the "South Complex" study area (Figure 1), which is an area situated between the Wyman Creek Cu-Ni Prospect (to the north) and the Boulder Lake area (to the south). Most of these holes (112 holes; 88,000 feet of core) have been relogged and correlated into several troctolitic to gabbroic stratigraphic sections. While each individual drilled area exhibits good correlative units in drill hole, these correlative units do not extend into an adjacent drilled area that is located a few miles distant. This lack of large-scale continuity suggests that either: 1) the "South Complex" study area constitutes an area that actually includes several smaller intrusive bodies; 2) drilling is not detailed enough to delineate large-scale correlative units; 3) the effects of contamination related to assimilation of footwall rocks close to the contact hampers large-scale correlations; or 4) combinations of the above.

In addition to exploration for Cu-Ni sulfide mineralization, many of the holes drilled in the "South Complex" area intersected smaller plug-like bodies of Oxide-bearing Ultramafic Intrusions (OUI); the distribution of large OUI bodies are shown in Figure 1. The OUI are characterized by coarse-grained to pegmatitic clinopyroxenite, picrite, peridotite, and dunite that are intrusive into the troctolitic rocks. Oxide content in the OUI varies from 15-20% (disseminated) to thick massive oxide zones. Ilmenite is the dominant oxide in some OUI; whereas, titanomagnetite is dominant in others. In almost all instances, the OUI are spatially arranged along linear trends suggesting that structural control was important to their genesis. At some localities, a genetic link between iron-formation assimilation at the basal contact and OUI formation is apparent (Longnose, Longear, and Section 17 bodies). This suggests that the OUI were initially formed at depth followed by upward injection of OUI material along fault zones. However, other OUI are situated within, or immediately below, layered oxide-rich gabbroic rocks (Boulder Lake area) suggesting that the OUI formed by a differentiated iron-rich melt that drained down into the cumulate pile along fault zones. Still other OUI do not show any immediate relationships to oxide-rich rocks present within either the footwall or surrounding troctolitic rocks and possible genetic links are unknown. Sulfide-mineralized zones are generally rare within the "South Complex" area. The highest amount of sulfides associated with troctolitic rocks are present in holes drilled in the Water Hen and Whiteface Reservoir areas (Figure 1).

Comparison of rock types on a geochemical basis is ongoing. The OUI are the most interesting of this group as each of the specific OUI bodies has a distinct geochemical "fingerprint" relative to each other. Each of the OUI also has significant variations in overall content of TiO_2 , V_2O_5 , Cr, Cu, Ni, and graphite due to dominant rock type, mineralogy, and geographic location. For example the southernmost OUI bodies generally have much higher V_2O_5 contents than the northernmost OUIs which contain higher concentrations of Cr, Cu and Ni. While graphite is common to most OUI, the Water Hen OUI is the only OUI that contains thick intersections of massive graphite (present in the upper half of the body). In some cases these variations reflect the dominant mineralogy; however, in some cases they may reflect different modes of origin (or differences in the footwall source rock or Complex host rock).



Geochemistry and fractionation of the Eastern Gabbro, Coldwell Alkaline Complex.

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The Eastern Gabbro is the oldest major intrusion in the 1108 ± 1 Ma Coldwell Alkaline Complex (CAC). It forms a ring-dyke surrounding a variety of lithologies ranging from quartz syenite to nepheline syenite. It is part of the first intrusive center in the CAC and is associated with iron-rich augite syenite, monzodiorite and basaltic xenoliths.

The Eastern Gabbro consists of four subunits, in order of emplacement these are, Gabbronorite (GN), Two Duck Lake Intrusion (TDLI), Layered Gabbro (LG) and Malpas Lake Intrusion (MLI). The rocks are plagioclase-rich cumulates that contain variable amounts of olivine, clinopyroxene, biotite, ilmenite, magnetite and orthopyroxene.

Rock and mineral Mg# and compatible elements decrease in abundance in the sequence GN - TDLI - LG - MLI. Incompatible elements eg alkalis, Ba, Zr and REE increase in the same sequence. There is however a great deal of overlap in the compositions of the GN, TDLI and LG indicating that they crystallised from magmas with similar compositions.

The composition of the magmas which crystallised to form the rocks of each subunit was estimated by analysis of fine-grained samples and weighted averaging. The estimated magma composition of

the TDLI and LG are similar to typical Keweenawan olivine tholeiites. The MLI estimate is rich in SiO_2 and alkalis and is akin to a Keweenawan basaltic andesite. The estimate for the GN is not used because it may have been contaminated by silica.

Modelling of fractionation in the Eastern Gabbro suggests that there is a differentiation trend from TDLI to LG and MLI. The similarities in major oxide composition of the TDLI and LG magmas and difference in trace elements rules out simple fractionation. A more complex model of fractionation in a replenished and erupting magma chamber is proposed. In this model fractionation is achieved by crystallisation of olivine, clinopyroxene and plagioclase in the ratio 1:4:6.7. The magma removed is evolved and the replenishing magma is the same composition as the original starting material. This model causes fractionation of trace elements but leaves the major elements relatively unaffected.

Using this model the LG was derived from the TDLI by 2-8 cycles of fractionation, eruption and replenishment. Continued fractionation of the LG leads to the MLI and eventually to the iron-rich augite syenite which intrudes the Eastern Gabbro.

ON THE ORIGIN OF ALKALINE GABBROIC ROCKS IN THE COLDWELL PENINSULA AREA, COLDWELL ALKALINE COMPLEX, ONTARIO.

Shore, Geoff T., Department of Earth Science, University of Western Ontario, London, Ontario, N6A 5B7. The Coldwell Peninsula Area (CPA) represents the southernmost extension of the Keeweenawan Coldwell Alkaline Complex (CAC) into Lake Superior. Arcuate bodies of nepheline syenite and alkaline gabbro dominate the CPA and together comprise the main lithologies within the second intrusive centre of the CAC. A zone of heterogeneous-textured alkaline gabbroic megaxenoliths, varying in composition from gabbro to olivine gabbro, occupies the central portion of the peninsula bounded to the north and south by later intrusions of nepheline syenite. The alkaline gabbroic xenoliths occur as blocks (< 1m to > 100m) formed by disruption, brecciation and assimilation of an early layered gabbroic body by later syenitic phases.

Several large layered alkaline gabbro megaxenoliths occur in the vicinity of Port Coldwell. The layered gabbroic sequences are cut by chemically and mineralogically similar, heterogeneous-textured gabbroic rocks. Early, rhythmically layered alkaline gabbroic megaxenoliths are fractionated with decreasing compatibles (Ni, Cr, Co) and increasing incompatibles (Zr, Y, Th, Nb, Ba) and alkali elements towards the south.

Spectacular breccia zones, comprised of lobe and cusped microgabbroic enclaves surrounded by a nepheline syenite host, are the result of nepheline syenite magmatism and synplutonic microgabbroic dykes. Whole rock and mineral geochemistry is consistent with derivation of the synplutonic microgabbroic enclaves through olivine (Fo_{87}), clinopyroxene ($\text{En}_{43}\text{Wo}_{48}\text{Fs}_8$) and plagioclase (An_{67}) fractionation of a primitive alkali basaltic parent. Microgabbroic enclaves and syenites form linear trends on Mg# versus major element (Na, K, Ca, Al) and trace element (Ni, Co, Zr, Nb, Ba, Rb) plots suggesting that at least some of the enclaves are related to the syenites by assimilation.

A four-stage model is proposed to explain the emplacement history of the main units within the CPA: 1) emplacement of centre 1 lithologies and initiation of alkaline gabbro fractionation; 2) disruption of the layered alkaline gabbro sequence and intrusion by cognate alkaline gabbro magma; 3) nepheline syenite intrusion and *in situ* differentiation; 4) amphibole natrolite nepheline syenite and synplutonic microgabbroic dyke intrusion.

WILLIAMS MINE

By: Gordon Skrecky, James Gray, and Allan Guthrie

REGIONAL GEOLOGY

The Williams Mine lies on the south side of the essentially east-west trending Schreiber-White River Greenstone Belt of Archean volcanic and sedimentary rocks. The belt has been subjected to regional metamorphism, up to amphibolite grade. It is interpreted as being synclinally folded. Granitic intrusions and gneissic bodies bound the belt to the north and south and intrude the synclinal axis of the belt.

In the vicinity of the Williams Mine the supracrustal rocks are divided into the Playter Harbour Group and Heron Bay Group. The former is primarily composed of mafic volcanic rocks and the latter primarily of felsic volcanic rocks and metasedimentary rocks with minor intrusive rocks. The Heron Bay Group dips to the north, structurally overlies the Playter Harbour Group, and contains all the economic gold deposits found to date near Hemlo.

PROPERTY GEOLOGY

The major rock units on the property strike 108° and dip from 60° to 70° to the northeast. The general property stratigraphy from south to north is mafic metavolcanic rocks, lower metasedimentary rocks, an altered felsic porphyry rock unit, the gold mineralized rocks, and the upper metasedimentary rock sequence. An intermediate to felsic fragmental unit separates the upper metasedimentary unit from the felsic porphyry unit on the western portion of the property. Lower and upper denote the relative structural positions of the metasedimentary rock units as the younging directions are unclear. An intermediate intrusive unit divides the felsic porphyry unit into two segments at the east end of the property. All of the major rock units are highly deformed.

The major intrusive rocks, in decreasing order of age, are intermediate to felsic dikes and felsic porphyry dikes, altered, biotite-rich dikes, diabase, and lamprophyre. All of these intrude the orebody and the basic stratigraphy. A mafic intrusive pipe-shaped body cuts the felsic porphyry rocks in the 'C' zone pit and is in turn cut by later diabase diking.

The diabase dikes and younger lamprophyres are Proterozoic. In contrast to the intermediate and felsic dikes which are conformable to the stratigraphy, they fill joints trending north and dipping very steeply east and cut the earlier dikes.

THE MAIN OREBODY

The main orebody has a strike length of about 1200 m, dips at 60° to 70° to the northeast and plunges to the northwest at approximately 45° . It outcrops at surface and continues to a vertical depth of about 1300 m on the Williams property. Upon crossing a claim line to the east it becomes the Golden Giant deposit of Hemlo Gold.

The maximum thickness of ore is 45 metres and is located adjacent to the Hemlo Gold boundary. Moving west from that property boundary, the ore generally declines in width and grade. The western portion of 'B' zone reserves, from about the proven/probable line through the possible category, incorporates two ore-grade zones within the typical host lithology. These are separated by an internal waste pillar of at least 10 metres horizontal thickness. This mineralization represents the fringe of the 'Hemlo Deposit' and as such, continuity of ore grade and thickness become increasingly erratic.

Williams Operating Corporation treated 2.3 million tonnes of ore to produce 445,000 ounces of gold in 1994, making it one of Canada's largest gold mines. Total Proven and Probable Ore Reserves totalled at 30.9 million tonnes grading 5.7 grams of gold per tonne at the end of 1994.

EFFECTS OF LARGE METEORITE IMPACTS ON CRUSTAL ROCKS - SUDBURY BASIN IN THIN SECTION

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The origin of the Sudbury Igneous Complex (SIC), in central Ontario, has been a subject of controversy for over ninety years.

Since 1962 more recent detailed field and laboratory studies by Dietz, Guy-Bray, Peredery, Dence, Dressler and many others have greatly strengthened the impact theory as the trigger mechanism for the Sudbury event. The Sudbury impact occurred during an active Penokean orogeny about 1.85 b.y. ago [1]. One of the interesting questions arising from the impact-theory is how much of the SIC might be impact melt rather than internally derived igneous rock material?

Presence of shock metamorphic features have been observed by recent research in the footwall of the SIC (Dence 1972, Guy-Bray and INCO Geological staff 1966, Dressler 1984) and in the breccias of the Onaping Formation (French 1968, 1970, 1972, Peredery 1972, Muir and Peredery 1984). These features include: shatter cones, microscopic planar elements in quartz and feldspar, plastic deformation of feldspar, kink bands in biotite mica, severe fracturing of garnet, recrystallized quartz and glasses, and incipient melt bodies.

Commonly found associate feature near impact sites are Shatter-cones. Shatter-cones are radial fracture surfaces with striae that fan from an apex (Dietz 1968, 1972). The striae are sharp grooves between intervening, rounded ridges developed by pressure releases upon impact. Shatter-cones can be found around the SIC for distances as much as 17 km away.

Studies indicate (von Engelhardt et al. 1969, Stöffer 1967, Chao 1968, Dressler 1970) that shock pressures weaker than 100 kilo-bars do not produce any typical shock-metamorphic features. Shock experiments using plagioclase feldspar [2] produced planar features between 150 and 300 kilo-bars pressure. Between 300 and 500 kilo-bars pressure, whole plagioclase crystals became diaplectic glass (maskelynite) and above 500 kilo-bars, normal glass of plagioclase composition was formed. The corresponding working temperature reached during the active stage of the SIC can be estimated from the work of Naldrett and Kullerud (1967)[3]. They concluded that the SIC at its norite intrusion activity level reached temperatures of 1000°C with a 20°C per 1 km geothermal gradient at an emplaced depth of 5 km. From the extent of the pyroxene-hornfels facies of 220 metres from the SIC, these researchers estimated that the SIC remained at temperatures of about 600°C for more than 720,000 years after the norite intrusion.

Some 23 representative field samples from the SIC [4] were collected along with several samples of Shatter-cones for thin-sectioning followed by microscopic examination. Field samples include: Shatter-cones (Map Loc #1,2), Sudbury Breccia North-range (Loc #4), Sudbury Breccia South-range (Loc #6), Footwall Breccia (Loc #8,9,10), North-range Onaping Formations Basal Member (Loc #11A), Gray Member (Loc #11B), Melt Body (Loc #11C), Black Member (Loc #13), South Range-Basal Member (Loc #14), Chelmsford (Loc #16), Onwatin Formation (Loc #17), SIC member Norite (Loc #19), SIC-member Sublayer (Loc #20), and Nickel-copper sulphide sample from the discovery site at Murray Mine Open pit (Loc #23).

Shock metamorphic features can be viewed in thin sections of these samples. Sections of Shatter-cones show the extent of the obliteration of quartz grains along the pressure fractures occurring in arenite material. Similar features as shatter-cones but not formed in the usual conical pattern were found in the Basal member of the Onaping Formation on the south range at sample site #14 south of Vermillion Lake. This hands-on poster display provides a window to some of the Sudbury Igneous Complex rock units and their unique inherent mineralogy.

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The Geco Mine, Manitouwadge, Ontario: a volcanogenic massive sulphide deposit

H. Lockwood presented by: I. Wolfson
Hemlo Gold Mines, Inc. Golden Giant Mine, Hemlo, Ontario

The Geco Division of Noranda Mining and Exploration Inc. began production in 1957. To date, over 53 million tons of ore grading 1.85% copper, 3.78% zinc, 0.30% lead, 1.64 ounces per ton silver and 0.004 ounces per ton gold have been produced, worth over 5 billion dollars at 1994 prices. The orebody was discovered by 3 prospectors in 1953.

Geco now consists of an underground mine with 125 miles of lateral drives serviced by two shafts, a concentrator and supporting plant installations. The mine currently produces 80,000 tons of ore per month. Most ore now comes from remnants and pillars using the Geco Running Tight Fill stoping method, which uses immediate rock fill to stabilize weak stope walls as ore is removed. 260 people are employed. Copper and zinc concentrates averaging 29% copper and 55% zinc respectively are shipped by rail to Noranda's smelters in Rouyn and Valleyfield, Québec. The mine will close in late 1995.

Geco's main ore zone consists of a massive coarse-grained pyrite-pyrrhotite-sphalerite-chalcopryite core enveloped by stringer pyrite-pyrrhotite-chalcopryite ore in a silicified sericite schist unit. The stringer ore margins are defined by assay, currently 2% copper. The main ore zone has a surface strike length of 2,400 feet, an average width of 65 feet, and plunges east at 40 degrees to 3450 feet below surface. The sulphide-rich orebody grades laterally into a siliceous magnetite-rich iron formation. Two narrow copper and zinc-rich stringer zones (4/2 copper and 8/2 zinc zone) total 3 million tons of marginal ore and are found on the lower and upper contacts of the sericite schist unit respectively.

The main ore zone grades laterally eastward into a siliceous banded quartz-magnetite iron formation which has been followed for 15 miles with diamond drilling; several other ore zones (Willroy, Willecho and Nama Creek) have been located to the west on or near the Geco productive horizons in the 10 by 15 mile area of folded supracrustal rocks that comprise the Manitouwadge Camp.

The silicified sericite schists that host Geco's ore are underlain by orthoamphibole-biotite-garnet-cordierite gneisses, which are interpreted as hydrothermally altered mafic to intermediate volcanics. This group extends several miles laterally, and there does not appear to be any particular alteration pattern within it immediately underlying the Geco ore zone. The deposit is overlain by varying textures of quartz-feldspar-biotite gneisses, interpreted as volcaniclastic metasediments, with intercalated volcanics, quartz-magnetite iron formation (locally zinc-rich) and tonalitic intrusions.

PROPOSED FIELD TRIPS FOR THE 42nd ANNUAL INSTITUTE ON LAKE SUPERIOR GEOLOGY

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U. S. Geological Survey; ¹St. Paul, MN, ²Reston, VA; ³UW Oshkosh, Oshkosh, WI

The 42nd Annual Institute on Lake Superior Geology will be held in Cable, Wisconsin from 15 May to 19 May, 1996. In keeping with tradition, two days of technical session on May 16 and 17 will be bracketed by pre-meeting and post-meeting field trips. The field trips will cover a wide range of interests, from the metamorphosed and deformed Archean to the most recent geological manifestations of the last glaciation. The field trips will highlight results of recent geologic efforts in northern Wisconsin by the U. S. Geological Survey, the Wisconsin Geological and Natural History Survey, and the staff at the active Flambeau massive sulfide mine. Six possible field trips are currently planned but the final selection will depend on the interest level for each trip. All of the field trips are within easy travel distance from the Institute headquarters at the Telemark Lodge, Cable, Wisconsin, allowing maximum time in the field.

Geology of the South Limb of the Midcontinent Rift, North-Central Wisconsin

Bill Cannon, Suzanne Nicholson, Laurel Woodruff, U. S. Geological Survey

Rocks of the Midcontinent Rift dated at 1.1 Ga cover much of northern Wisconsin. Geologists at the U. S. Geological Survey have remapped the region as part of the Metallogeny of the Midcontinent Rift Project, providing new insight into the structure, geochemistry, and stratigraphy of the rift. The area of this field trip near Mellen, Wisconsin, provides a complete stratigraphic cross section of the rift, from pre-rift Bessemer Quartzite through the syn-rift Freda Sandstone and includes the intrusive Mellen Complex, which strongly influenced the development of the rift in this region as both a volcanic source and a thermal and structural high.

From the Middle Proterozoic to the Archean: A 25 km section of the crust

Bill Cannon, U.S. Geological Survey

A 25-km thick monoclinical succession of vertical to steeply dipping strata is exposed between the shore of Lake Superior and the Gogebic iron range in northern Wisconsin. The monocline was created by crustal-scale thrusting shortly after formation of the Midcontinent rift. The trip will traverse 'downward' through the crust from the Freda Sandstone, through the Middle Proterozoic Keweenawan Supergroup, Early Proterozoic strata of the Gogebic iron range, and end in Late Archean volcanic rocks. This is one of the most complete sections of the upper and middle crust exposed on earth.

Geology and Environmental Impact of the Flambeau Mine, Ladysmith, WI

Staff Geologists of the Flambeau Mine

The open pit Flambeau mine, operated by Flambeau Mining Company, a wholly owned subsidiary of the Kennecott Corporation, is developed in a zone of

Late Proterozoic supergene enrichment on an Early Proterozoic volcanogenic massive sulfide deposit. Copper is extracted from chalcocite, bornite, and chalcopyrite in the supergene zone. Gold is mined separately from an overlying, gold-rich gossan. The development of the project employs the latest environmental controls of massive sulfide exploitation. The mine is scheduled to close in 1997 and the area restored to its pre-mining condition. This field trip will include a visit to the working face of the open pit and a detailed look at the environmental aspects of the mine.

Early Proterozoic Strata of the Marquette Range Supergroup, MI and WI

Gene LaBerge, University of Wisconsin, Oshkosh, John Klasner, Western Illinois University, and Bill Cannon, U.S. Geological Survey

Early Proterozoic strata of the Marquette Range Supergroup comprise a 2-3 km-thick sedimentary sequence recording sedimentation successively on a stable craton, passive margin, and compressional foreland. Recent detailed mapping has led to new insight about the depositional environments and post-depositional deformation of the various units, which include the Bad River Dolomite, the Palms Formation, the Ironwood Iron-Formation, and the Tyler Formation. As many as three possible trips may be developed from the recent work; these would examine the eastern part of the section in Michigan, the western part of the section in Wisconsin, and a cross-section near the Penoque Gap, emphasizing the structural deformation and stratigraphic relations.

Glacial Geology of Northwestern Wisconsin

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This field trip will investigate the margin of the Superior lobe of late Wisconsinan age in northwestern Wisconsin, looking at landforms (tunnel channels, eskers, hummocks, ice-walled-lake plains) and typical sediment types (Cooper Falls till, outwash, and lake sediment). The trip will also look at the Spooner Hills, a band of high-relief, eroded hills, built by catastrophic releases of subglacial meltwater. Finally, one stop will be devoted to highlighting the history of glacial lakes in the Clam-Yellow-River lowland.

Sulfide Mineralization in Basalts of the Midcontinent Rift

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Preliminary field studies on the north limb of the Ashland syncline in northern Wisconsin has revealed widespread copper sulfide mineralization in basalt quarries of the Middle Proterozoic Chengwatana Volcanics. Mineralization has been found in numerous quarries and natural exposures. Chalcopyrite, bornite, and chalcocite occur mostly in amygdules and open space filling in altered fragmental basalt flow tops, in much the same manner that native copper occurs in correlative basalts of the Keweenaw Peninsula. This field trip will visit several exposures displaying various aspects of this little-known type of mineralization.

GEOLOGICAL SETTING AND GEOCHEMISTRY OF MASSIVE SULPHIDE DEPOSITS AND ALTERATION ZONES IN THE MANITOUWADGE GREENSTONE BELT, NORTHWESTERN ONTARIO

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The base-metal deposits of the Manitouwadge greenstone belt provide a classic example of the difficulties encountered in petrogenetic studies of mineralization in complex metamorphosed and polydeformed terranes. The Manitouwadge belt is a highly deformed remnant of supracrustal rocks in the volcano-plutonic Wawa subprovince, immediately south of the major tectonic boundary with the metasedimentary-migmatitic Quetico subprovince (see the figure in Peterson et al., this volume). The map pattern is determined by regional D3 folds, including the Manitouwadge synform. D1 and D2 structures repeat mineralized and altered horizons. Our understanding of the depositional setting and genetic relationships of the base-metal deposits, alteration zones and host rocks, depends on unravelling the effects of ductile deformation and metamorphic recrystallization.

The belt comprises a mafic-to-felsic volcanic succession, in which felsic rocks are interleaved with iron formation and massive sulphide deposits. Greywackes, previously assumed to reflect a transition from volcanism to clastic sedimentation (Friesen et al., 1982), are at least 25 Ma younger than the 2720 Ma felsic volcanism and probably a tectonic enclave of Quetico rocks (Zaleski et al., 1995). A synvolcanic trondjemite intrusion was a reservoir for felsic volcanism and heat source for hydrothermal activity. All rocks have been metamorphosed to upper amphibolite facies, including two zones of synvolcanic hydrothermal alteration, now characterized by metamorphic minerals. Orthoamphibole±garnet±cordierite gneiss forms a stratabound sheet of regional extent, mantling synvolcanic trondjemite in the stratigraphic footwall (structural hanging wall) to the mineral deposits. The unit is primarily defined on the presence of orthoamphibole-bearing assemblages, which are interleaved with sillimanite-cordierite-biotite±garnet layers. Hornblende-plagioclase±orthoamphibole±cummingtonite±garnet assemblages become more common away from known mineral deposits and are interpreted as less intensely altered mafic rocks. The precursors to alteration, recognizable in less altered enclaves, were mafic and interlayered mafic-felsic rocks near the transitional mafic-felsic contact. The second alteration unit, sillimanite-muscovite-quartz schist, occurs in close proximity to massive sulphide deposits, mostly in the stratigraphic hanging wall (structural footwall). It also envelopes some orebodies including the largest in the belt, the Geco main orebody. The precursor to alteration was felsic volcanic rock found along-strike and in less altered enclaves.

The Geco, Willroy, Nama Creek and Willecho massive sulphide deposits lie in the northern part of the southern limb and hinge region of the D3 Manitouwadge synform (see the figure in Peterson et al., this volume). A D1 fault divides the area into two tectonic blocks and repeats part of the mineralized sequence. In the Willecho area, original stratigraphic relationships are further obscured by D2 folds of the D1 fault and mineralized sequence. The structural complexity can be partly resolved by examining the characteristics of orebodies and mineralized horizons. Based on Cu-Zn-Pb proportions, nature of mineralization, and relationships to iron formation and alteration zones, the orebodies of the Manitouwadge camp can be divided into three main types. Firstly, Cu-rich stringer/disseminated orebodies lie in the orthoamphibole-garnet-cordierite footwall and, in the Geco area, surround the main orebody in sillimanite-muscovite-quartz schist. Secondly, massive and semi-massive Zn-Cu-(Pb) orebodies are hosted by iron formation and enveloped by sillimanite-muscovite-quartz schist, or interleaved with schist and quartz-phyric felsic rocks. This group includes the two largest orebodies; the Geco main and Willroy #3 orebodies. Thirdly, massive and semi-massive Zn-Pb-(Cu) orebodies, interpreted as highest in the stratigraphy, are hosted by iron formation that overlies sillimanite-muscovite-quartz schist.

Despite the unusual extent and concordance of alteration zones at Manitouwadge, geochemical trends from 'least-altered' to intensely altered, such as increase in $\text{FeO}_t + \text{MgO}$ and Al_2O_3 , and depletion in alkalis and CaO, are similar to those recorded in alteration pipes in the Abitibi camp (Riverin and Hodgson, 1980). All felsic extrusive rocks show evidence of potassic alteration; whereas, synvolcanic trondjemite apparently preserved its primary sodic composition. Similar observations of alkali exchange have been made in the Abitibi camp with respect to the synvolcanic Flavrian pluton and its extrusive equivalents (Goldie, 1979). 'Immobile' elements in altered

rocks at Manitouwadge tend to define bimodal populations that mimic element abundances in mafic and felsic precursors. The bimodal distribution shows that orthoamphibole-garnet-cordierite rocks and sillimanitic interlayers had both mafic and felsic protoliths; the metamorphic assemblage was determined by small variations in $(\text{FeO}_t + \text{MgO})/\text{Al}_2\text{O}_3$, apparently due to alteration and not inheritance from the protolith.

The unusual extent of orthoamphibole-bearing gneiss at Manitouwadge may be partly due to the high metamorphic grade. With increasing grade, orthoamphibole-hornblende stability expands the range of orthoamphibole-bearing assemblages to more calcic bulk-rock compositions (Spear, 1993, pages 478–489). By inference, bulk-rock compositions that produced orthoamphibole-bearing rocks at Manitouwadge might, at lower metamorphic grade, be considered incipient alteration. The closest analogues for the stratabound regional orthoamphibole-bearing alteration are found in the Bergslagen area of the Svecofennian Baltic shield. At Bergslagen, exhalative base-metal deposits and iron formation are underlain by conformable stratabound Mg-rich alteration zones of regional extent (Trägårdh, 1988; Ripa, 1988; Baker et al., 1988). Amphibolite-facies metamorphism at Bergslagen may play a role, as at Manitouwadge, in facilitating identification of altered rocks. However, in both areas, it appears that alteration was partly focussed on aquifer horizons possibly consisting of permeable, poorly consolidated volcanoclastic deposits.

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DERIVATIVE CONTINENTAL INDICATIONS OF A CURVILINEAR CARIBBEAN MANTLE CONVECTION PLUME

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Inextricably interrelated to the recurved-bow interpretation of the MRS development, is introduced a second hypothesis, proposing that when the Iowa bow initially fractured, its continental territory was positioned over a distinctively curvilinear array of related mantle convection upwelling, which originally established and continues to define the perimeter margins of the eastern end of the Caribbean plate. The ancient formation of this curvilinear plume's characteristic arc shape is reasoned, by rationale and evidence, to exhibit a coriolis influence, upon its early convection's melt flow.

The emergent scenario is that after the Iowa bow fracturing of this first continental superposition, the plume remained stationary while the continent was moved about 160 km, possibly by the collision of the Grenville Province. Subsequently, the movement subsided and a second rift system developed, which is indicated today by the clear delineation of the same plume profile by derivative aeromagnetic effects from the attendant surface rifting; and by a second recurved bow in southern Michigan, which is symmetrically coincident to the rift pattern, and exhibits both a stressfully significant 90 degree alignment to the Iowa bow, and is concordant with it in curvature phase with respect to the interior side of the same rift pattern. This unique orientation is an extremely significant evidential correlation between the recurved-bow hypothesis and the Caribbean convection plume hypothesis, as it lends validity to both the proposed mechanisms by graphically illustrating the interrelationship between the two developments. Also, supporting consistent pattern correspondence, the paleogeographic position of the length axis of the Iowa bow, paleomagnetically matches the Caribbean plate's northern margin.

Could a curvilinear mantle convection plume, positioned under the Caribbean plate, have created these continental and oceanic crustal pattern replications? It is suggested that, as a composition implies a history, the coincidence of three physical matchings of derivative effects in accessible proximity, begs for thoughtful consideration of a common causal source.

A CONTINENTAL CRUST FRACTURE INITIATION PATTERN AND HYPOTHETICAL MECHANISM

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A careful observation of the North American Midcontinent Rift System (MRS) as detailed on a Bouguer gravity map filtered to exclude features with wavelengths greater than 250 km, reveals a distinctive symmetry and geometric regularity between southern Minnesota and southeastern Nebraska. The symmetry expressed is reflected relative to both a primary axis oriented from the NW to the SE, and a secondary axis oriented orthogonally. The axes of symmetry on the map's surface, are interpreted to represent the intersections of two orthogonal radial planes of reflection with the spherical crustal surface. The observed symmetrical pattern of rift curvature suggests a causal relational influence superimposed upon the fracture formation process by some compelling features or events located nearby, and within these two radial planes of reflection. This is because, mechanistically, simple natural symmetry is the physical manifestation of spatial pattern that reflects an invariance of distance dependent causal relationship.

It is hypothesized that the crust fracture curvature is the product of a curvilinear array of related mantle convection upwelling aligned under the secondary axis, that produces tension and other convection related stresses in the crust. The symmetrical curvature produced by the initial propagation of crustal fracture under these stresses, exhibits a profile very similar to an archer's recurved bow. This figure is a surface expression of an extensional crust fracture regime, and delineates an initial penetrating normal fault which later bounded an upwelling decompression melt. It is further proposed that the entire rift fracture started with this figure, that the curvature results from an elastic strain release of regional crustal material during its fracture, and that similar signature profiles have past recorded occurrences worldwide.

A tensive, adjunctive emergence of a triple junction of fracture is offered to supplant its previously imagined role in the rift's creation and growth. The signature bow fracture hypothesis is further supported by evidence of the regular appearance of several collateral features which are logically related to the bow's development and have been noted at other suspected bow fracture locations. Thus, from the creative application of pattern recognition with a mechanistic understanding of simple natural symmetry, and giving consideration to geometric material stress projection, a hypothetical fracture development is presented.