

39th ANNUAL



INSTITUTE ON LAKE SUPERIOR GEOLOGY

EVELETH, MINNESOTA

MAY 5-8, 1993



Organized by:
Minnesota Geological Survey
with cooperation from:
Minnesota Department of
Natural Resources, Minerals Division
and
Mesabi Range Geological Society

Proceedings Volume 39
Part 1 - Program and Abstracts

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**INSTITUTE ON
LAKE SUPERIOR GEOLOGY**
Proceedings Volume 39

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Organized by:

Minnesota Geological Survey

General Chair: David L. Southwick

Program Chair: Jane Cleland

Field Trip Chair: Mark Jirsa

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and***

Mesabi Range Geological Society

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INSTITUTES ON LAKE SUPERIOR GEOLOGY

Institute Number	Date	Place
1	1955	Minneapolis, Minnesota
2	1956	Houghton, Michigan
3	1957	East Lansing, Michigan
4	1958	Duluth, Minnesota
5	1959	Minneapolis, Minnesota
6	1960	Madison, Wisconsin
7	1961	Port Arthur, Ontario
8	1962	Houghton, Michigan
9	1963	Duluth, Minnesota
10	1964	Ishpeming, Michigan
11	1965	St. Paul, Minnesota
12	1966	Sault Ste. Marie, Michigan
13	1967	East Lansing, Michigan
14	1968	Superior, Wisconsin
15	1969	Oshkosh, Wisconsin
16	1970	Thunder Bay, Ontario
17	1971	Duluth, Minnesota
18	1972	Houghton, Michigan
19	1973	Madison, Wisconsin
20	1974	Sault Ste. Marie, Ontario
21	1975	Marquette, Michigan
22	1976	St. Paul, Minnesota
23	1977	Thunder Bay, Ontario
24	1978	Milwaukee, Wisconsin
25	1979	Duluth, Minnesota
26	1980	Eau Claire, Wisconsin
27	1981	East Lansing, Michigan
28	1982	International Falls, Minnesota
29	1983	Houghton, Michigan
30	1984	Wausau, Wisconsin
31	1985	Kenora, Ontario
32	1986	Wisconsin Rapids, Wisconsin
33	1987	Wawa, Ontario
34	1988	Marquette, Michigan
35	1989	Duluth, Minnesota
36	1990	Thunder Bay, Ontario
37	1991	Eau Claire, Wisconsin
38	1992	Hurley, Wisconsin
39	1993	Eveleth, Minnesota

CONSTITUTION OF INSTITUTE ON LAKE SUPERIOR GEOLOGY

- Article I Name
The name of the organization shall be the "Institute on Lake Superior Geology".
- Article II Objectives
The objectives of this organization are:
- A. To provide a means whereby geologists in the Great Lakes region may exchange ideas and scientific data.
 - B. To promote better understanding of the geology of the Lake Superior region.
 - C. To plan and conduct geological field trips.
- Article III Status
No part of the income of the organization shall inure to the benefit of any member or individual. In the event of dissolution the assets of the organization shall be distributed to _____ (some tax free organization).
- (To avoid Federal and State income taxes, the organization should be not only "scientific" or "educational", but also "non-profit".)
- Minn. Stat. Anno. 290.01, subd. 4
Minn. Stat. Anno. 290.05(9)
1954 Internal Revenue Code s.501(c)(3)
- Article IV Membership
The membership of the organization shall consist of the board of directors. Any geologist interested shall be permitted to attend and participate in and vote at the annual meetings.
- Article V Meetings
The organization shall meet once a year, preferably during the month of April. The place and exact date of each meeting will be designated by the board of directors.
- Article VI Directors
The board of directors shall consist of the Chairman, Secretary-Treasurer, and the last three past Chairman; but if the board should at any time consist of fewer than five persons, by reason of unwillingness or inability of any of the above persons to serve as directors, the vacancies on the board may be filled by the annual meeting so as to bring the membership of the board up to five members.

Article VII Officers

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

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

Article VIII Amendments

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

BY-LAWS

I. Duties of the Officers and Directors

- A. It shall be the duty of the Annual Chairman to:
 - 1. Preside at the annual meeting.
 - 2. Appoint all committees needed for the organization of the annual meeting.
 - 3. Assume complete responsibility for the organization and financing of the annual meeting over which he presides.
- B. It shall be the duty of the Secretary-Treasurer to:
 - 1. Keep accurate attendance records of all annual meetings.
 - 2. Keep accurate records of all meetings of, and correspondence between, the board of directors.
 - 3. Hold all funds that may accrue as profits from annual meetings or field trips and to make these funds available for the organization and operation of future meetings as required.
- C. It shall be the duty of the board of directors to plan locations of annual meetings and to advise on the organization and financing of all meetings.

II. Duties and Expenses

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

III. Rules of Order

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

IV. Amendments

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

Award Guidelines SAM GOLDICH MEDAL

Preamble

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

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

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

Award Guidelines

- 1) The medal shall be awarded annually by the I.L.S.G. Board of Directors to a geologist whose name is associated with a substantial 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

STUDENT TRAVEL AWARD

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

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

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

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

BOARD OF DIRECTORS

- 1993 David L. Southwick**
Minnesota Geological Survey, St. Paul, Minnesota, 55114
- 1992 Albert B. Dickas**
University of Wisconsin-Superior, Superior, Wisconsin, 54880
- 1991 P.E. Meyers**
Department of Geology, University of Wisconsin, Eau Claire, Wisconsin
54701
- 1990 M.M. Kehlenbeck**
Department of Geology, Lakehead University, Thunder Bay, Ontario P7B
5E1
- Permanent Secretary-Treasurer**
M.G. Mudrey, Jr.
Wisconsin Geological and Natural History Survey
3817 Mineral Point Road, Madison, Wisconsin 53705

LOCAL COMMITTEE

- D.L. Southwick**
General Chairman, Minnesota Geological Survey, St. Paul, Minnesota 55114
- J.M. Cleland**
Program Committee and Proceedings Editor, Minnesota Geological Survey,
St. Paul, Minnesota 55114
- M.A. Jirsa**
Field Trip Committee, Minnesota Geological Survey, St. Paul, Minnesota 55114
- G.B. Morey**
Treasurer, Minnesota Geological Survey, St. Paul, Minnesota 55114

GOLDICH MEDAL COMMITTEE 1992-93

- H.H. Halls (1993)**
Department of Geology, Erindall College, Mississauga, Ontario L5L 1C0
- R.D. Sage (1994)**
Ontario Geological Survey, 777 Grenville Street, Toronto, Ontario M7A
1W4
- Glen Adams (1995)**
3030 S. Rifle Road, Rhinelander, Wisconsin 54501

GOLDICH MEDAL RECIPIENT

Donald W. Davis

Department of Geology, Royal Ontario Museum,
100 Queen's Park, Toronto, Ontario M5S 2C6

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 Halls
1988	Walter White
1989	Jo Kalliokoski
1990	Kenneth C Card
1991	William J. Hinze
1992	William F. Cannon
1993	Donald W. Davis

BANQUET SPEAKER

Robert Zierenberg

JOI/USSAC Distinguished Lecturer, U.S. Geological Survey, Menlo Park,
California. *Implications for massive sulfide genesis from ODP leg 139
drilling in Middle Valley, northern Juan de Fuca Ridge.*

38th Annual Institute on Lake Superior Geology Hurley, Wisconsin

The 38th Annual Meeting of the Institute on Lake Superior Geology was conducted from May 7 through May 8, with pre-session field trips held on May 6, and post-session trips conducted May 9, 1992. Co-hosts for this meeting were the University of Wisconsin-Superior and the Wisconsin Geological and Natural History Survey. Albert B. Dickas acted as the General Chairman, while M.G. Mudrey, Jr. coordinated the technical session as Program Chairman, and Bruce A. Brown organized the four field sessions as Field Trip Chairman. Proceedings of the 38th conference were published in two parts: Volume 38, Part 1 contains the program and abstracts, while Volume 38, Part 2 contains the field guides for the four conference field trips.

The technical sessions and annual banquet were held in the Holiday Inn, Hurley, Wisconsin. An off-campus site was selected for the 38th session in order to minimize travel distances to the field trip sites. A total of 151 geologists were registered, 108 of whom attended the Thursday evening banquet. The technical session portion of the program was composed of 30 oral papers and 16 poster paper presentations.

Two pre-session field trips were conducted on Wednesday, May 6:

1. Archean and Early Proterozoic geology of the Gogebic district, northern Michigan and Wisconsin, led by Gene L. LaBerge and Richard W. Ojakangas.
2. Keweenawan sedimentary rock of the south shore, Lake Superior, led by Albert B. Dickas and M.G. Mudrey, Jr.

After the conclusion of the technical session the following additional trips were conducted:

3. Geology of Keweenawan Supergroup rocks near the Porcupine Mountains, Ontonagon and Gogebic counties, Michigan, led by William F. Cannon, Suzanne W. Nicholson, Cheryl A. Hedgman, Laurel G. Woodruff, and Klaus J. Schulz.
4. Geology of the Great Lakes Tectonic Zone in the Marquette area, Michigan - a Late Archean paleosuture, led by P.K. Sims and Z.E. Peterman.

A total of 119 individuals attended these field trips, including those who participated in two field trips. In addition to the field trip leaders, acknowledgment and kudos are given to Randy Maass and Walter Hall (of the Wisconsin Geological and Natural History Survey) and Nick Van Wyck (University of Wisconsin - Madison) for their valuable assistance during both the technical and field trip sessions.

One hundred and eight (108) were in attendance at the Thursday evening banquet. The speaker was Mr. Duff Kerr, oil and gas consultant from Denver, Colorado. Mr. Kerr spoke on his decade-long involvement in exploration for hydrocarbon along the western arm of the Midcontinent Rift System. Prior to this presentation, Paul K. Sims, USGS, Denver, Colorado, presented the 1992 Goldich Medal to William Cannon, of the USGS, Reston, Virginia for his many contributions to the better understanding of the geology of the Lake Superior Basin.

Student travel awards totaling \$975 were awarded to 6 individuals giving papers: Michelle Barnes, Brad Hellickson, Stanley Radsevicius, Georgia Osborn, Mark Davidson and Xinpeng Yin. Two \$150 awards were offered for best oral and poster student awards to David J. Allen and Andrew O. Moshonian. The judge for these awards was Dr. Penelope C. Morton, University of Minnesota - Duluth.

The Institute on Lake Superior Geology Board of Directors met in Hurley, Wisconsin on May 8, 1992. In attendance were M.G. Mudrey, Jr., Albert B. Dickas, Bruce Brown, M.M. Kehlenbeck, G.B. Morey, David Southwick, Paul Myers, L.S. Chan, and Richard W. Ojakangas. The following items made up the working agenda:

1. 1993 Meeting

The site of the 1993 meeting will be at the Holiday Inn, Eveleth, Minnesota, May 5-8. Principle host will be the Minnesota Geological Survey, in cooperation with the Minnesota Department of Natural Resources, the Mesabi Range Geological Society, and the Minnesota Exploration Association. Organizers for the Minnesota Geological Survey will be David Southwick (General Chairman), Jane Cleland (Program Chair), and G.B. Morey.

2. Treasurer's Report

- a. Goldich account: 8% CD #40221 due 8-29-93
- b. General account: 6.05% CD #43157 due 9-7-92
- c. Checking account:
- d. Cash

Total a, b, c and d as of 1991: \$10,669.17

Increase 1991-1992

\$2000 advance to P. Meyers, with
\$3,288.63 returned plus increase
from investments of \$422.20 2,810.83

Total Account ~~\$13,480.00~~ 13510

From all accounts, the 1992 ILSG meeting was a success. Thank you to all who helped bring about this success.

Albert B. Dickas, General Chairman, ILSG 1992



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Calendar of Events and Program

Wednesday, May 5

Field Trip 1	Geology of iron mines in the eastern and central Mesabi range. Leaders: R. Waidler, R. Graber, and R.W. Ojakangas
8:00 am	Registration and departure, Holiday Inn lobby
5:30 pm	Return
4:00-9:00 pm	Registration and check-in, Holiday Inn lobby
7:00-11:00 pm	Icebreaker (cash bar) Poster session, Room A

Thursday, May 6

7:15 am	Registration, Holiday Inn lobby
Session 1:	Morey, G.B., and Ojakangas, R.W., session chairs (8:00-10:45 am)
8:15 am	WELCOME
8:20 am	Card, K.C., and Percival, J.A. <i>An Archean Unconformity in the Vizien Greenstone Belt, Ungava Peninsula, Quebec</i>
8:40 am	Jirsa, M.A. <i>Structural & Stratigraphic Framework of the Western Wawa & Quetico Subprovinces - Cook to Side Lake Area, Minnesota</i>
9:00 am	Hudleston, P.J. <i>Significance of Strain Patterns in Archean Greenstone Belts</i>
9:20 am	Coffee break
9:40 am	Bornhorst, T.J. <i>Lead Isotope Data for Galena from the Copps Mine, Gogebic County, Michigan</i>
10:00 am	Grant, J.A. <i>Isocon Analysis of Chemical Changes in Migmatites and Paleosols</i>
10:20 am	Severson, M.J. <i>Igneous Stratigraphy of the Partridge River and South Kawishiwi Intrusions - Duluth Complex, Northeastern Minnesota</i>

Field Trip 2	Core displays in conjunction with MDNR open house & lunch. Leaders: M. Severson, G.B. Morey, H. Dahlberg, D. Martin, and G. Meyer
11:00 am	Registration and departure to DNR Core Library, Holiday Inn lobby.
2:00 pm	Return to Holiday Inn
12:15 pm	Institute on Lake Superior Geology Board of Directors Luncheon (by invitation)
Session 2:	Brown, B.A., and Luther, F.R., session chairs (2:00-5:00 pm)
2:00 pm	Cannon, W.F., Nicholson, S.W., Zartman, R.E., Peterman, Z.E., and David, D.W. <i>The Kallander Creek Volcanics -- A Remnant of a Keweenawan Central Volcano Centered near Mellen, Wisconsin</i>
2:20 pm	Wilson, G.C., Pavlish, L.A., Ding, Gang-Jian, and Farquhar, R.M. <i>Precious-Metal Content and Textural Features of Native Copper and Copper Artifacts from the Great Lakes Region</i>
2:40 pm	Horton, R.J. <i>Prehistoric Copper Mining in the Lake Superior Basin</i>
3:00 pm	Chandler, V.W. <i>Geophysical Studies in the Duluth Area, Northeastern Minnesota</i>
3:20 pm	Coffee break
3:40 pm	Miller, J.D., Jr. <i>Evidence of Interruptions During the Fractional Crystallization of the Duluth Complex Layered Series at Duluth</i>
4:00 pm	Allen, D.J., and Chandler, V.W. <i>Magnetic Properties of the Midcontinent Rift Volcanics at Osseo, Minnesota: Clues to the Origin of Aeromagnetic Anomalies</i>
4:40 pm	Green, J.C. <i>Stratigraphy and Volcanology of the North Shore Volcanics in the Duluth Quadrangle</i>
6:15-7:15 pm	Mixer, cash bar
7:15-10:00 pm	Annual Banquet Announcement of the 40th Annual Meeting location. 1994 Goldich Award presentation to D.W. Davis by K.D. Card. Banquet speaker: Robert Zierenberg, JOI/USSAC Distinguished Lecturer, U.S. Geological Survey, Menlo Park, California <i>Implications for massive sulfide genesis from ODP leg 139 drilling in Middle Valley, northern Juan de Fuca Ridge</i>

Friday, May 7

- 8:00 am Registration, Holiday Inn lobby
- Session 3:** Cannon, W.F., and McSwiggen, P.L., session chairs (8:20 am-12:00 pm)
- 8:20 am Ojakangas, R.W.
Sedimentology and Provenance of the Early Proterozoic Michigamme Formation and Goodrich Quartzite, Northern Michigan: Regional Stratigraphic Implications and Suggested Correlations
- 8:40 am Hemming, S., Hanson, G.N., McLennan S.M., Southwick, D.L., and Morey, G.B.
Nd Isotopic Constraints on the Provenance of Early Proterozoic Sediments and the Locations of Tectonic Boundaries in Central Minnesota
- 9:00 am Brown, B.A., and Maass, R.S.
Brecciated and Silicified Felsic Volcanic Rocks of Late- or Post-Penokean Age in Central Wisconsin
- 9:20 am Hayes, M.J., and Nelson, C.L.
Computer Modeling in the Geosciences: Emphasis on Aeromagnetic Data—Techniques and Interpretations
- 9:40 am Van Wyck, N., and Johnson, C.
Early Proterozoic Ages from Central Wisconsin
- 10:00 am **Coffee Break**
- 10:20 am Arias, Z.G., and Helmstaedt, H.
Structural Evolution of the Michipicoten Greenstone Belt, Superior Province: Evidence for an Archean Fold and Thrust Belt
- 10:40 am Cleland, J.M.
Occurrence and Implications of Tourmaline-Rich Rocks in the Trommald and Mahnomen Formations of the Cuyuna Range, East-Central Minnesota
- 11:00 am Muhich, T.G.
Movement of Ti Across the Duluth Complex—Biwabik Iron Formation Contact at Dunka Pit, Mesabi Iron Range, Northeastern Minnesota
- 11:20 am Schmidt, P.G.
Nature and Age of the Vermilion Fault System, Northern Minnesota
- 11:40 am **Lunch Break**

- Session 4:** Cleland, J.M., and Runkel, A.C., session chairs (1:02-2:20 pm)
- 1:20 pm Kean, W.F.
Magnetic Studies of the Keweenaw Age Chengwatana Lava Flows near Dresser Wisconsin
- 1:40 pm Lavigne, M.L., and Scott, J.F.
The North Coldstream Mine, Burchell Lake, Northwestern Ontario
- 2:00 pm Smyk, M.C., and Taylor, R.P.
Preliminary Investigations of the Nicopor Copper-Nickel Prospect, Northwestern Ontario
- 2:20 pm **Coffee Break**
- Session 5:** Lehman, E., and Dahlberg, H., session chairs (2:40-4:40 pm)
- 2:40 pm Alminas, H.
Geochemical Studies in the Vermilion District and the Duluth Complex, Northeastern Minnesota -- A Progress Report
- 3:00 pm Nichol, I.
Geochemical Exploration for Base and Precious Metals using Glacial Till
- 3:20 pm Averill, S.
The Role of Reverse Circulation Drilling in the Discovery of Mineralization Covered by Deep Glacial Deposits
- 3:40 pm Spector, A.
Bedrock Geology in the Shephard Area Deduced from Geophysical Data; Implications for Minerals Exploration
- 4:00 pm Ikola, R.J.
Gravity Anomalies over Wisconsin Massive Sulphide Deposits
- 4:20 pm Adams, G.
Mineral Exploration Techniques in Deeply Buried Terranes: Means to Discoveries in the U.S. Lake Superior Region
- Field Trip 3** **Archean greenstone granite terrane in the Cook-Side Lake area.**
Leaders: M.A. Jirsa, T.J. Boerboom, and P.L. McSwiggen
- 8:00 am Registration and departure, Holiday Inn lobby
- 5:30 pm Return

Field Trip 4 Type section of the Duluth Complex at Duluth.
Leaders: J.D. Miller, Jr., V.W. Chandler, and J.C. Green

8:00 am Registration and departure, Holiday Inn lobby

5:30 pm Return

Poster Session

Bauer, R.L.

Late-Tectonic Thermal Overprint on Syntectonic Regional Metamorphism in the Northwestern Quetico Subprovince, Northeastern Minnesota

Boerboom, T.J.

Anatomy of a Shear Zone: Textural & Geochemical Changes in Sheared Ferrodiorite, Northern Wawa Subprovince, Minnesota

Brink, S.

Petrographic Evaluation of Ore Textures from Manganiferous Iron Formation and Copper-Oxide Porphyry for In Situ Mining Potential

Brown, B.A., and Maass, R.S.

Occurrence and Carbon Isotopic Composition of some Wisconsin Graphites

Cambry, F.W., Hodder, R.W., and Scott, G.W.

Reactivated Archean Structures, Proterozoic Stratigraphy and Mineral Deposits; Western Upper Michigan

Dean, M.C., and Craddock, J.P.

Outcrop Offsets and Microscopic Kinematic Indicators in a Proterozoic Mafic Dike-Strike Fault Array, Black River Falls, Wisconsin

Frey, B.A.

Central Minnesota Drill Core Logging and Assay

Handke, M.J., and Palmquist, J.C.

Ultramafic Lamprophyre dikes with Carbonatitic Affinities near Marquette, Michigan; Evidence in Support of the Thiel Fault and a Trans-Superior Tectonic Zone

Heine, J.J.

Kaolin Resources in Minnesota

Hinz, P.

Exploration and Mining Activities of Industrial Minerals in Northwestern Ontario

Lawler, T.L.

Summary of Current Work in Central Minnesota and Future Plans

- Luther, F.R.
A Metamorphosed Dike in the Precambrian Waterloo Quartzite, Old Portland Quarry, Dodge County, Wisconsin
- Maass, R.S., and Brown, B.A.
Early Proterozoic Magmatism and Tectonism Related to Southward-Dipping Subduction and Microcontinental Accretion in Central Wisconsin
- McGovern, M.G., Craddock, J.P., and Webers, G.F.
Evidence for Late Paleozoic Displacement on the Keweenawan Thrust Fault from Folded Paleozoic Outliers in Michigan's Upper Peninsula
- Oberhelman, M.W., and Riihiluoma, R.
Dimension Stone Inventory of Northern Minnesota
- O'Brien, M.S., Lavigne, M.J., and Smyk, M.C.
Exploration and Mining Activity in Northwestern Ontario
- Oreskovich, J.
Kittson County Bloating Clays
- Runkel, A.C., Morey, G.B., Lively, R.S., and Mossler, J.H.
Outlying Mississippi Valley-Type Sulfide Mineralization, Fillmore County, Minnesota
- Zaleski, E., and Peterson, V.L.
Lithotectonic and Structural Setting of Mineralization in the Manitouwadge Greenstone Belt, Northwestern Ontario
- Zbikowski, D.
A Continental Crust Fracture Initiation Pattern and Hypothetical Mechanism
- Zielinski, A.M., Mancuso, J.J., Frizado, J.P., and Waidler, R.J.
Manganese-rich Oncolites in the Biwabik Iron Formation, Thunderbird Mine, Mesabi Iron Range, Minnesota



ABSTRACTS

MINERAL EXPLORATION TECHNIQUES IN DEEPLY BURIED TERRANES; MEANS TO DISCOVERIES IN THE U.S. LAKE SUPERIOR REGION

ADAMS, Glen W., Geological Consultant, 3030 South Rifle Road,
Rhineland, WI 54501

The southwest continuation of the Canadian Shield in the U.S. Lake Superior region has been explored for base- and precious metals for over 40 years. Discoveries have been limited to areas of scattered outcrop in Minnesota and Upper Michigan, and to Proterozoic terranes of relatively shallow glacial cover in Wisconsin. Though some areas of shallow cover have potential for discovery, the more deeply covered, less explored, terranes are the current target areas.

Exploration styles and techniques have evolved to deal with exploring in deeply buried terranes. Strongly conductive overburden, areas of increased cultural interference, and more subtle targets are typical problems. Regional target selections still utilize conventional data sets. However, new data processing and other technological advancements are used to extract and display previously concealed characteristics and, hopefully, improve geological understanding.

Project-scale target definition and detailed individual target evaluation also benefit from enhanced data collection and data manipulation techniques. Specific projects from the U.S. Lake Superior region exemplify the use of enhanced lithological and structural information obtained from state-of-the-art, satellite remote sensing-, airborne-, and ground-derived data. Enhancement and imagery are set aside for the final, and telling, evaluation tool – the drill rig.

Present-day exploration realities, including anti-development legislation, environmental restrictions, and the lure of foreign exploration, present "deep" formidable obstacles. They are undermining domestic exploration confidence and are critically affecting exploration in difficult terranes.

To maintain exploration interest in deeply buried terranes, highly technical and sophisticated exploration techniques must be merged with down-to-bedrock data gathering and persistence. Of equal importance, exploration must be stimulated by pro-development/pro-environment political atmospheres. Nothing, however, does more for difficult exploration terranes than a metal discovery. Areas of high discovery potential in the U.S. Lake Superior region are discussed.

MAGNETIC PROPERTIES OF THE MIDCONTINENT RIFT VOLCANICS AT OSSEO, MINNESOTA: CLUES TO THE ORIGIN OF AEROMAGNETIC ANOMALIES

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The high-resolution aeromagnetic surveying program of the Minnesota Geological Survey (Chandler, 1991) has provided an opportunity to conduct a detailed investigation of the Chengwatana Volcanic Group of the Midcontinent Rift System. Particularly useful are a series of alternating positive and negative high-frequency linear anomalies (Fig. 1). These anomalies are continuous for up to 50 km and, where the Chengwatana Group is exposed, trend parallel to the strike of the volcanic beds. This correlation has been useful for mapping packages of volcanic rocks in the subsurface and for identifying internal structures within the St. Croix Horst (Allen and Chandler, 1992). Thus far, however, the aeromagnetic data have been interpreted in a qualitative manner only. To discover the actual sources of the high-frequency linear anomalies, detailed magnetic modeling, combined with magnetic properties measurements, is essential.

In 1975, Northern Natural Gas drilled a deep well into the northwest margin of the pre-Paleozoic Twin Cities Basin near Osseo, MN (T119N, R22W, S24; see Fig. 1). The well penetrated nearly 1.0 km into the Precambrian basement and, with the exception of relatively minor interflow sedimentary units, the entire interval consisted of basaltic volcanic rocks (average flow thickness ~60 ft). Over 3200 ft (0.98 km) of continuous core was recovered (presently housed at the Minnesota DNR Drill Core Library in Hibbing, MN). This core provides a unique opportunity to investigate the magnetic properties of the Midcontinent Rift volcanic rocks. The core penetrates a thick, continuous section of basalts and is more representative than surface samples, which are often heavily weathered and represent very limited stratigraphic intervals.

Figure 2 is a magnetic log of the Northern Natural Gas well. Magnetic susceptibility was measured every 2 ft along the core using a hand-held susceptibility meter. The log indicates two broad intervals of relatively high susceptibility separated by regions of low susceptibility. In addition, natural remanent magnetization (total NRM, including all primary and secondary components) was measured for 32 samples throughout the well using a spinner magnetometer. All of the samples were normally polarized. Similar patterns of alternating high and low NRM intensity were observed. The variations in susceptibility and NRM intensity are not correlated with obvious physical or chemical alteration, suggesting that they may be related to magma chemistry.

Variations in magnetization such as those shown in Figure 2 are a likely candidate for the source of the observed high-frequency linear aeromagnetic anomalies (Fig. 1). For example, the beds in the well near Osseo dip ~25° to the southeast; hence, the volcanic units in the well (and their associated magnetizations) project up to the pC-C surface, resulting in horizontal magnetization variations. For a dip of 25°, the horizontal distance between the two intervals of higher magnetization is ~1 km, compared to the observed 1-3 km separation between the crests of the positive aeromagnetic anomalies.

To critically evaluate the relation between the measured magnetizations and the observed aeromagnetic anomalies, detailed magnetic models have been constructed. Inclusion of remanent magnetization is critical to the models, as the basalts from the Northern Natural Gas well have strong remanent magnetizations, with an average Q (ratio of remanent to induced magnetization) of nearly 5.

Density and P-wave velocity were also measured for samples from the Northern Natural Gas well. Dry density was measured using a Jolly balance. The average density for 32 samples is 2950 kg/m³. Moreover, the distribution is relatively narrow; 22 of the samples have densities between 2900 and 3000 kg/m³. Compressional wave velocity was measured (at 2 kbar confining pressure) for 7 samples. Velocities range from 6.07 to 6.75 km/s, with an average of 6.50 km/s. Velocity and density are positively correlated.

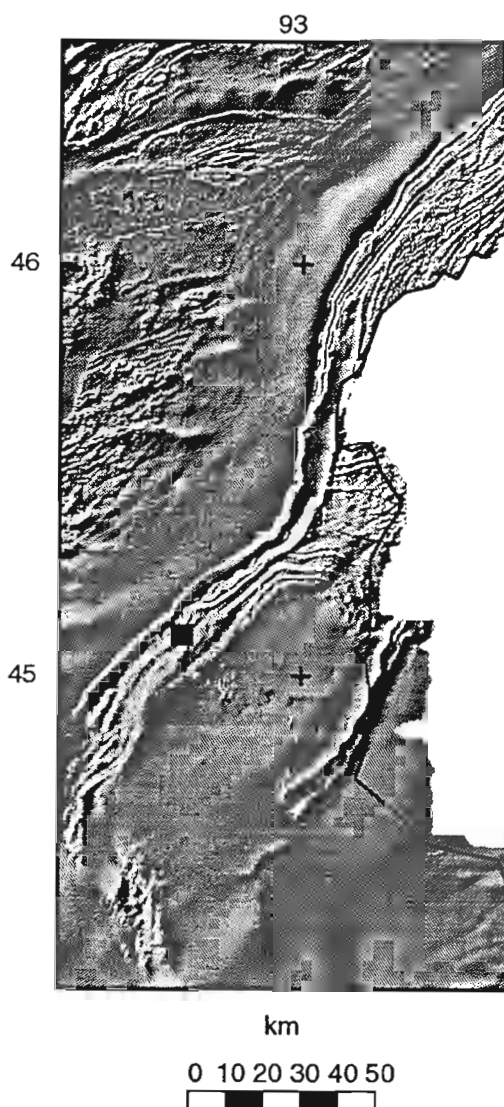


Figure 1: Shaded relief presentation of aeromagnetic data for east-central Minnesota (sun from northwest). Black square indicates deep well near Osseo, MN.

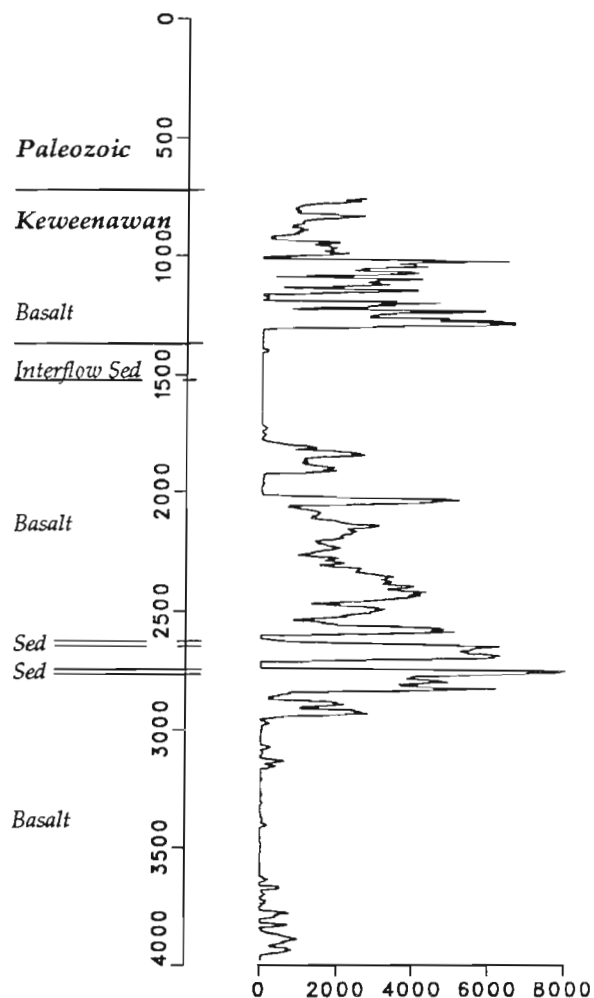


Figure 2: Magnetic susceptibility ($\times 10^{-6}$ emu/cc) vs. depth (ft) for the Northern Natural Gas well near Osseo, MN.

REFERENCES

- Allen, D.J., and Chandler, V.W., 1992, The utility of high-resolution aeromagnetic data for investigating the Midcontinent Rift in east-central Minnesota, [abst.]; Institute on Lake Superior Geology Proceedings, 38th Annual Meeting, Hurley, WI, 1992; v. 38, part 1, p. 3-5.
- Chandler, V.W., 1991, Aeromagnetic anomaly map of Minnesota: Minnesota Geological Survey State Map Series S-17, scale 1:500,000.

GEOCHEMICAL STUDIES IN THE VERMILION DISTRICT AND THE DULUTH COMPLEX, NORTHEASTERN MINNESOTA -- A PROGRESS REPORT

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Geochemical studies in the Vermilion district were carried out in three stages. The initial study, in the west-central part of the Vermilion district, extends from the central part of Lake Vermilion in the west to Moose Lake in the northeast. Here, 754 sites were sampled in an area encompassing some 568 km² within St. Louis, Lake and Cook Counties.

The sampled area is centered on the Archean greenstone belt of the Vermilion district. This belt consists predominantly of mafic metavolcanic and associated rocks that were intruded on both the north and south by major granitoid bodies. Approximately 90 percent of the Ely Greenstone rocks are of basaltic composition; the remainder are intermediate to felsic volcanic rocks, hypabyssal intrusive rocks, banded iron formation, chert, and metasedimentary rocks. A-horizon soils, developed from Pleistocene glacial materials consisting of till, outwash and lacustrine deposits of the Wisconsin episode of glaciation, were sampled in addition to outcrops.

This study indicates that two major areas within the west-central part of the Vermilion district are mineralized with respect to precious- and base-metals. The more pronounced one is centered on Lake Vermilion. Gold contents of the soils are as high as 1.1 ppm and the gold is associated with Ag, Cu, Ti, Co, Pb, Zn, Co, Cr, Ni, La, V and Y. Mineralized rock is restricted primarily to the felsic volcanoclastic units. A pronounced anomalous aeromagnetic high, apparently related to the Lost Lake syenitic, granitic, and lamprophyric intrusive bodies immediately to the west of Lake Vermilion, shows a good spatial correlation with the areas of mineralization.

The second gold-bearing area is in the east end of the study area between Fall and Jasper Lakes. Gold is associated with Cu, Ti, Mn, Ag, Co, Mo, Ni, Sc, Zn, and V. Lamprophyric and syenitic intrusive rocks are present in the central part of this mineralized area and this area is essentially coextensive with a pronounced aeromagnetic anomaly.

The two geochemical anomalies indicate that widespread precious- and base-metal mineralization occurred in the Vermilion district. This mineralization appears to be related to the buried epizonal granite and syenite in the Lake Vermilion area, as well as to lamprophyric rocks intruded into the Lake Vermilion Formation and Ely Greenstone during the Algonian orogeny. Northeast-trending faults also appear to be factors in localizing the mineralization, especially in the eastern part of the greenstone belt.

Striking similarities are evident between the geologic, structural, and geochemical features of the Vermilion district and comparable features described by A.C. Colvine and others relative to the Archean lode gold deposits in Ontario.

The second stage of the study was initiated by the USGS in 1991 and encompasses some 414 km² immediately to the west of the first study area extending westward to Cook. In this stage delineation of the Lake Vermilion precious- and base-metal anomalies was completed. In addition, the eastern ends of two precious metal anomalous trends were delineated. The first, and more pronounced one, swings to the east of Lost Lake and continues westward over Pevla, Angora and Sturgeon. The second geochemical lineament is in the northern part of the study area and extends along a west-northwesterly trend from Black Duck Island (in Lake Vermilion) toward and past Haley.

The third stage of this study, carried out by the D.N.R., involved collection of a B-horizon soil and outcrop samples at 751 sites in an area of approximately 1,000 km² extending westward to Togo. The two geochemical lineaments detected in the second stage

of this study were extended to the western edge of the study area. At this time, data resulting from stages two and three are being evaluated and interpreted.

The Duluth Complex geochemical study incorporates 1,520 B-horizon soil samples and 516 outcrop samples collected in an area of some 1,798 km² in the northwestern part of the Duluth Complex. The soils were derived from Pleistocene glacial materials consisting of till, outwash, and lacustrine deposits associated with the Wisconsin episode of glaciation.

The Duluth Complex encompasses approximately 6500 km² of upper Precambrian anorthositic, troctolitic, gabbroic, granodioritic, and granitic intrusive rocks. It is exposed sporadically along an arcuate belt extending from Duluth north toward Ely and then north-northeast toward Hovland. The complex is underlain to the north and west by older Precambrian rocks, and the contact separating the older rocks from those of the Duluth Complex is generally sharp and well defined.

The study area includes all of the Hoyt Lakes-South Kawishiwi area and a small part of the Boundary Waters Canoe Area, as defined by Weiblen and Morey (1975), as well as some adjacent areas to the east.

The soil geochemical patterns detected in the northwestern part of the Duluth Complex are products of the predominant and very pronounced leaching and associated residual enrichment processes operating in this area modified by more subdued and local hydromorphic recharge from underlying bedrock, especially in areas of mineralized bedrock.

Geochemical patterns in the modern B-horizon soils within the study area show little evidence of glacial displacement. This is especially true of ore metals related to sulfides. Copper-related geochemical soil anomalies are immediately over and adjacent to the Duluth Complex contact rather than being displaced in the direction of glacial movement. Gold, in soils, also occurs within the same general contact area, although a second, more pronounced gold-related geochemical lineament occurs along an aeromagnetic anomaly extending from Bald Eagle Lake through Greenwood Lake.

Mineralogical (SEM-EDS, XRD) studies on some 70 diamond drill core samples, 15 outcrop samples and about 30 soil samples from the Duluth Complex indicate the presence of complex and multiple-stage mineralization episodes. Of particular noteworthy interest is the presence of a water-soluble, complex base- and transition-metal chloride-carbonate mineral assemblage. Iron-, magnesium-, and sodium-chloride-carbonate-hydroxide minerals are predominant; however, Pb-, Sn-, Ag-, Cu- and other chloride-carbonate-hydroxide species are locally abundant. These minerals occur as multi-colored (brown, orange, white, blue and green) efflorescences. Similar Pb-, Sn-, Cu- and Ag-chloride bearing minerals were noted from outcrop samples in the Vermilion district. Most of these minerals are apparently new to science.

References cited:

- Colvine, A.C., Fyon, J.A., Heather, K.B., Soussan Marmont, Smith, P.M., and Troop, D.G., 1988, Archean lode gold deposits in Ontario: Ontario Geological Survey Miscellaneous Paper 139, 136 p.
- Weiblen, P.W., Morey, G.B., 1975, The Duluth Complex -- A Petrologic and Tectonic Summary: Minnesota Geological Survey Reprint Series 28: 48th Annual Meeting, Minnesota Section American Institute of Mining Engineers, 1975.

STRUCTURAL EVOLUTION OF THE MICHIPICOTEN GREENSTONE BELT, SUPERIOR PROVINCE: EVIDENCE FOR AN ARCHEAN FOLD AND THRUST BELT

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The ca. 2.7 to 2.9 Ga Michipicoten greenstone belt extends northeast from Michipicoten Bay in northeastern Lake Superior, near Wawa, Ontario. Lithologic contacts within the belt were traditionally interpreted as primary depositional contacts juxtaposing continuous cycles of volcanism and sedimentation (Goodwin, 1962, Sage, et al, 1987). The thick supracrustal sequence was thought to have been folded in response to crustal disturbances related to batholithic intrusions. A detailed structural study by McGill and Shradly (1986) in the southern part of the belt, demonstrated the tectonic nature of some lithologic contacts and suggested a more complex deformation sequence involving early recumbent folding and inferred thrusting.

The present structural study indicates the presence of inverted (downward-facing) regional folds (F_2) that have refolded the overturned limb of a belt-scale recumbent nappe structure (F_1), exposed at the present level of erosion. The nappe was also imbricated along thrust faults related to the D_2 folding event (Figure 1; Arias and Helmstaedt, 1990).

Figure 1 is a deformed-state, composite structural cross section across the central part of the belt, showing the earliest recognized structural elements. Field observations show that the metasedimentary rocks in the central part of the belt unconformably or disconformably overly intermediate to mafic metavolcanic rocks, and represent the youngest rocks in the section. The depositional unconformity is structurally overturned up to 45 degrees. A major fault (southernmost fault shown in Figure 1) separates the overturned, southward-younging volcanic-sedimentary sequence from a geologically similar, overturned (in the immediate vicinity of the fault), northward-younging sequence of rocks. This configuration defines a regional, faulted, inverted syncline (F_2) for the southern part of the section (x-y). The geometry of the northern part of the section (y-z), based on the regional map pattern, is that of an inverted anticline (F_2).

On the basis of kinematic analyses in fault zones along the regional F_2 synclinal fold hinge, and along some lithologic contacts, the faults are interpreted as south-verging thrusts. Repetition of rock units within the overturned limb of the nappe (F_1) can be attributed to imbrication along the D_2 thrust faults. Consequently, the youngest supracrustal rocks, formerly interpreted as a thick stratigraphic sequence of two volcanic cycles (Goodwin, 1962, Attoh, 1980, Sage, et al, 1987), represent a single lithologic package that was highly deformed and thickened by structural stacking.

On the local scale, the regional strike of the rock units is subparallel to the axial surfaces of prominent F_2 folds. The limbs of these folds are typically sheared off parallel to their axial surfaces along F_2 -related imbricate thrusts. Younging reversals along the F_2 axial surfaces (S_2) indicate the presence of earlier folds (F_1), only locally associated with an S_1 cleavage. These folds may represent minor folds in the overturned limb of the recumbent nappe structure.

Locally, normal faulting ensued, recognized adjacent, but parallel, to the D_2 thrusts. The D_2 folds and related thrusts, as well as the local normal faults, are affected by east-northeast-striking shear zones (D_3) which, depending on the strike of the D_2 thrusts, have either dextrally offset or reactivated (at least) the thrusts as oblique-slip faults. The D_2 shear zones are similar to gold-hosting shear zones studied in the east-central part of the belt (Arias and Heather, 1987). All earlier structures are overprinted by a northeast-striking crenulation cleavage (S_4) and minor folds that do not significantly alter the map pattern.

Imposition of D₄ is interpreted to be responsible for the variability in plunge of F₂ fold hinges.

The field evidence supports a south-vergent fold and thrust geometry (D₂) imposed upon a belt-scale nappe (D₁), inferred to be also south-vergent, consistent with the northward subduction-island arc accretion model suggested for the Superior Province (see Card, 1990). The regional nappe represent the earliest recognized major deformation event. Pre-nappe deformation, as well as the nappe geometry, cannot be readily discerned by structural analysis, as the map pattern is dominated by the post-nappe fold and thrust geometry. Hence, it can only be stated that most similar, as well as diverse, rock assemblages involved in the formation of the nappe were at least structurally continuous (Arias and Helmstaedt, 1990).

In contrast to the downward-facing, thrust-faulted syncline and minor folds shown in the south part of the section, the geometry across the southwest strike extension of the southern fault (Figure 1) was interpreted by McGill (1992) as the product of south-verging convergence of two distinct volcano-sedimentary terranes along a south-vergent thrust. McGill (1992) interpreted that this convergence formed upward-facing folds (called nappes) overturned to the south.

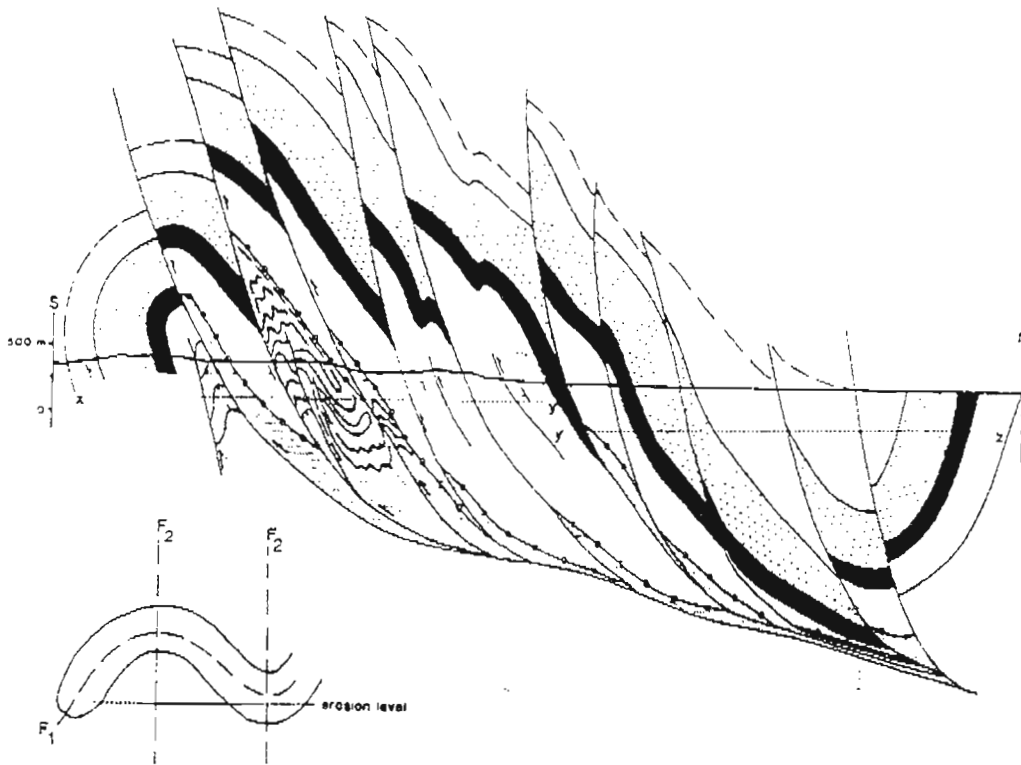


Figure 1. Composite structural section through the central part of the Michipicoten greenstone belt. Section X-Y is an admissible section based on the present work. Section Y-Z is a schematic section based on compilation. Mafic volcanics are shown blank, felsic volcanics in broad stipple, iron formation in black, and sedimentary rocks in dense stipple (grey). The sketch (lower left) explains the present configuration of the belt as a regional nappe (F₁) refolded about F₂. Imbricate thrusts are considered related to F₂.

References Cited

- Arias, Z.G., Helmstaedt, H., 1990. Structural evolution of the Michipicoten (Wawa) greenstone belt, Superior Province; Evidence for an Archean fold and thrust belt. In Geoscience Research Grant Program, Summary of Research 1989-1990. Ontario Geological Survey, Miscellaneous Paper 150, p. 107-114.
- Arias, Z.G., Heather, K.B., 1987. Regional structural geology related to gold mineralization in the Goudreau-Lochalsh area, Michipicoten greenstone belt. In Summary of Field Work and Activities 1987; Ontario Geological Survey, Miscellaneous Paper, P. 146-154.
- Attoh, K., 1980. Stratigraphic relations of the volcanic-sedimentary successions in the Wawa greenstone belt, Ontario. In Current Research, part A, Geological Survey of Canada, Paper 80-A, p. 101-106.
- Card, K.D., 1990. A review of the Superior Province of the Canadian Shield, a product of Archean accretion; Precambrian Research, 48, p. 99-156.
- Goodwin, A.M., 1962. Structure, stratigraphy and origin of iron formations, Michipicoten area, Ontario, Canada; Geological Society of America Bulletin 73, p. 561-586.
- McGill, G.E., Shradly, C.H., 1986. Evidence for a complex Archean deformational history, southwestern Michipicoten greenstone belt, Ontario; Journal of Geophysical Research B, 91, p. E281-E289.
- McGill, G.E., 1992. Structure and kinematics of a major tectonic contact, Michipicoten greenstone belt, Ontario; Canadian Journal of Earth Sciences, v. 29, n. 10, p. 2118-2132.
- Sage, R.P., Thorpe, R., Berdusco, E., 1987. Field trip guidebook- geology and stratigraphy of the Michipicoten iron formation; Institute on Lake Superior Geology, v.33, pt. 3, 93p.

THE ROLE OF REVERSE CIRCULATION DRILLING IN THE DISCOVERY OF MINERALIZATION COVERED BY DEEP GLACIAL DEPOSITS

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Thick or covered glacial till horizons in Canada are routinely sampled by reverse circulation drilling, and metal dispersal trains in the unweathered till are identified and traced to source by heavy mineral analysis. The Canadian technology should work well in the deeply covered glaciated terranes of the Lake Superior region, U.S.A.

The first reverse circulation drill rig for till sampling was designed in 1970 for VMS exploration by Texasgulf Sulphur Company and Bradley Brothers Drilling after Texasgulf observed well-mineralized till overlying glacially polished bedrock in the open pit of the world-class Kidd Creek deposit, Ontario. Another company using the same technology discovered a small Cu deposit (Currie-Bowman) three years later. VMS application for reverse circulation drilling was limited because most of the covered subcropping deposits had already been discovered by geophysics. In the late 1970's, reverse circulation drilling played a lead role in the discovery of Gulf Minerals' major Collins Bay B and Eagle Point uranium deposits in the Athabasca Basin, Saskatchewan, followed in the 1980's by the discovery of Inco's Golden Pond deposits in the Casa-Berardi gold district, Quebec. Principal current usage is for gold and diamond exploration and also in screening conductor swarms for possible VMS deposits "hidden" by extreme conductivity.

Reverse circulation drill rigs for till sampling are specially designed for all-terrain mobility and year-round operation under severe weather conditions. Ground pressure is sufficiently low for operation in environmentally realistic jurisdictions and a fluid containment system allows drilling on frozen lakes. Adjustable air-water flow and specially designed bits, subs and pipe ensure instant sample return with zero carry-over for accurate stratigraphic logging and dispersal train definition.

Dispersal trains in tills are typically 2 to 5 m thick; therefore a 1.5 m sample interval guarantees train detection in at least two consecutive samples in the drill hole. The detectable length of the train is maximized and drilling costs are minimized by using large samples (8 to 10 kg) and a high heavy mineral concentration factor (200 to 400:1). Typical train lengths are 0.5 km for gold, 5 to 15 km for VMS and U minerals, and tens of kilometers for kimberlite indicator minerals. The most useful indicators of source distance are: 1) the vertical separation of the train from bedrock; 2) the morphology of gold grains; 3) the particle size distribution of VMS and U mineral grains; and 4) the grain size of kimberlite indicator minerals and the degree of preservation of their surface resorption textures.

Although reverse circulation drilling is well established in Canada, it accounts for less than 1 percent of annual exploration expenditures. Accrued expenditures in 1993 Canadian dollars for all reversed circulation projects since 1970 are approximately \$35 million and the value of extractable metal in the three main discoveries (all viable mines) is \$3.1 billion. The average cost per discovery, including all geophysical surveys, diamond drilling and other work performed in conjunction with reverse circulation drilling projects since 1970, is about \$23 million compared to the average Canadian mine discovery cost of \$100 - 200 million.

LATE-TECTONIC THERMAL OVERPRINT ON SYNTECTONIC REGIONAL METAMORPHISM IN THE NORTHWESTERN QUETICO SUBPROVINCE, NORTHEASTERN MINNESOTA

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Metamorphism along the northern part of the Quetico Subprovince in Minnesota was initiated as an intermediate-pressure regional metamorphism that evolved spatially and temporally during the progress of three periods of folding and late syntectonic plutonism. Kyanite-staurolite grade metamorphic conditions were initiated in metasedimentary schists along the northern margin of the subprovince during the late stages of F_1 recumbent folding and the early stages of developing upright easterly plunging F_2 folds. Pressure conditions during this phase of the metamorphism were in the range of 5-6 kb. During the late stages of F_1 folding and the early stages of F_2 folding, white granite to granodiorite layers were intruded into the schist to the south of the northern boundary region. During progress of the F_2 folding, a high-grade Barrovian series of metamorphic zones developed from north to south across the area, ranging from the aforementioned kyanite-staurolite zone through sillimanite-staurolite, sillimanite-muscovite, and sillimanite-K-spar zones.

As the deformation progressed, pink biotite leucogranite of the Lac La Croix granite (LLG) batholith was emplaced along the southern margin of the study area, and large-scale upright F_2 folds were overturned to the south and refolded by a large-scale, upright, easterly plunging, F_3 anticlinorium. Continued metamorphic recrystallization during these late-stage events produced a thermal overprint on the regional metamorphism under conditions of decompression. This thermal overprint displays a complex spatial distribution that is related to structural position on the F_3 anticlinorium and proximity to the Lac La Croix batholith and its associated satellitic plutons. In the deeper levels of the anticlinorium, to the west, the Barrovian metamorphic sequence progresses from a broad sillimanite-muscovite zone along the northern limb of the anticlinorium to local sillimanite-K-spar zone assemblages and occurrences of cordierite + garnet + K-spar + sillimanite near phacolithic intrusions of LLG near the axial trace of the F_3 anticlinorium. At higher structural levels along the F_3 antiformal axial trace, to the east near the LLG batholith, staurolite of the sillimanite-staurolite zone is partially replaced by post- F_2 cordierite (+/-sill) or andalusite (+/-cord), and the width of the metamorphic zones is strongly telescoped. These observations are interpreted to be result of pronounced decompression heating along the F_3 antiformal axial trace during F_3 folding and intrusion of the LLG.

ANATOMY OF A SHEAR ZONE: TEXTURAL AND GEOCHEMICAL CHANGES IN SHEARED FERRODIORITE, NORTHERN WAWA SUBPROVINCE, MINNESOTA

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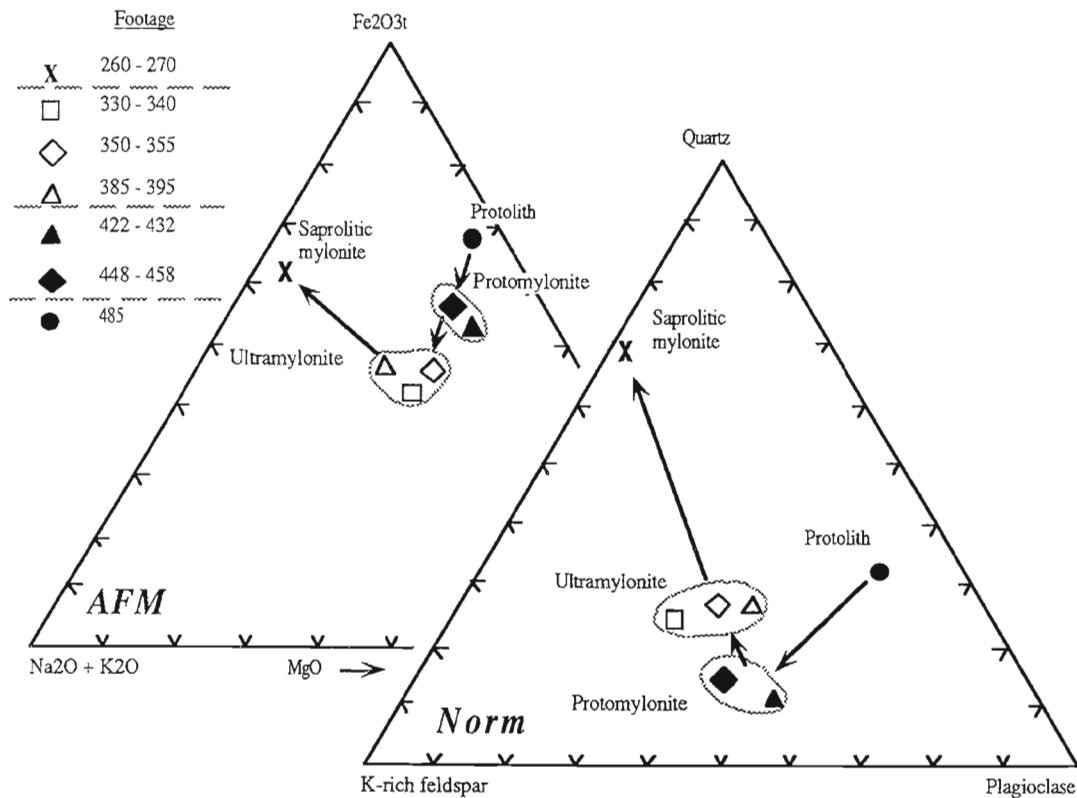
A diamond drill hole was drilled through a northeast-trending ductile ultramylonitic shear zone which cuts coarse-grained diabasic quartz ferrodiorite of Archean age. The drill hole was sited over a sharp, east-northeast-trending, strata-parallel, linear aeromagnetic anomaly, at the north edge of the Wawa granite-greenstone subprovince, near its boundary with the Quetico metasedimentary rock subprovince. The shear zone occurs within the Wawa subprovince, along a contact between felsic volcanogenic metasedimentary rocks to the north and ferrodiorite to the south, and was presumably localized by contrasting competencies between the two rock types. The ferrodiorite is inferred from geophysical data to be a folded sill at least 1500 feet thick within metasedimentary rock.

The bottom of the core is pristine in texture but retrograde altered, coarse-grained, quartz ferrodiorite with myrmekitic quartz-feldspar intergrowths. This grades upward to an ultramylonitic carbonate-quartz-chlorite-sericite schist that could easily be misinterpreted as a schist of sedimentary or felsic volcanic origin. The progressive upward increase in shearing intensity is well documented by skeletal crystals of ilmenite, which form black, equant grains up to 1 cm in size in pristine rock, but with the first indication of shearing become altered to leucoxene. These ilmenite pseudomorphs become progressively flattened uphole, and are eventually dismembered into tiny flecks which are visible in even the most mylonitized zones. Rhombic ankerite porphyroblasts, which postdate the bulk of deformation, are locally prominent as 1-mm porphyroblasts rimmed along the ends by fibrous quartz and chlorite. Late carbonate veinlets scattered throughout the core range from straight, brittle veins to elongate, deformed clots, suggesting that local ductile deformation overlapped with brittle vein emplacement. Quartz and carbonate locally occur in crack and seal shear veins.

Seven chemical analyses were obtained on core samples ranging from "fresh" (pristine in texture but retrograde altered) protolith at the bottom, through the mylonite, into saprolitic mylonite at the top. As shearing intensity increases, the general trend is a loss of Ca, Mg, $\text{Fe}_2\text{O}_3\text{T}$, and TiO_2 , and an increase in Na_2O , K_2O , Al_2O_3 , and P_2O_5 . SiO_2 shows a significant initial loss at the onset of shearing, but an increase thereafter. In the saprolitic mylonite at the top of the core, SiO_2 , K_2O , and Al_2O_3 increase markedly and TiO_2 and P_2O_5 increase slightly, whereas Na_2O , CaO , and MgO show a marked decrease. This differs from most deeply weathered saprolites, which typically are depleted in K_2O and SiO_2 , and suggests a pre-saprolite enrichment in those elements, perhaps through argillic alteration. On the AFM ($\text{Na}_2\text{O}+\text{K}_2\text{O}$ - FeOT - MgO) diagram, the sample that is least altered plots toward the F corner near the F-M join. Moderately sheared, protomylonitic samples define a subgroup that plots more toward the A corner, directly away from the F-M join as a result of gaining $\text{Na}_2\text{O} + \text{K}_2\text{O}$, and the remaining three ultramylonitic samples plot still farther toward the "A" corner, defining a third subgroup. The saprolitic sample is different from the others, plotting away from the M corner, because of relative depletion in Mg. Normative compositions on the alkali feldspar-quartz-plagioclase ternary diagram, define similar subgroups, first plotting near the Q-P join (higher SiO_2 and CaO), then trending toward the A corner (higher $\text{Na}_2\text{O} + \text{K}_2\text{O}$) as a result of the increasing proportion of alkalis. Again, the saprolitic sample plots well away from the other samples, toward the quartz corner of the diagram, as a result of its higher silica and lower calcium content.

The core was obtained as part of a multi-year scientific core drilling program to investigate selected aeromagnetic anomalies. This drill hole (number KDH-6, -60° inclination, 260° azimuth)

was cored from 212 to 520 feet in depth, as part of the 1989 program, which covered parts of Koochiching, Itasca, and Beltrami Counties. The drilling was funded by the Minnesota Legislature under the Minerals Diversification Program administered by the Minerals Coordinating Committee. Six of the geochemical analyses were provided by Newmont Exploration, Inc.



LEAD ISOTOPE DATA FOR GALENA FROM THE COPPS MINE, GOGEBIC COUNTY, MICHIGAN

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Quartz veins, usually barren, commonly cut Early Proterozoic strata of the Marquette Range Supergroup. Only two such veins in Upper Michigan are known to us to contain galena, one now inaccessible at the closed Tracy Mine in Marquette County and the other at the Copps Mine in Gogebic County. The Pb isotope composition of the Copps Mine galena is of interest in the context of new Pb isotopic data reported by Bornhorst and others (in review) from two discrete episodes of veins hosted by Archean rocks of the Ishpeming greenstone belt, Marquette County. Depending on the interpretation, Pb isotopic model ages for galena from the Ropes gold mine are 2360 to 2600 Ma (gold mineralization in the greenstone belt), whereas quartz-carbonate base metal-bearing (gold barren) veins are likely 1985 to 2287 Ma, although a somewhat younger age is possible (the latter veins cut gold mineralized rock). The Pb isotopic data from the Ishpeming greenstone belt provide the basis for interpreting data from the Copps Mine.

The Copps Mine is located in the SE 1/4, section 15, T. 47 N., R. 43 N. about 10 km NNE of Marenisco where quartz veins containing galena occur in Early Proterozoic sedimentary rocks in an area of complex structure and stratigraphy. The sulfide-bearing veins are hosted in a cherty zone where the Copps Formation (Baraga Group; Trent, 1973) greywacke appears to be in fault contact with the Palms Formation slate and quartzite and Ironwood Iron Formation (Menominee Group). Local exposures include the Sunday Quartzite and Bad River Dolomite (Chocoma Group) and mafic igneous rocks perhaps related to the Emperor Volcanics (LaBerge, 1992). Galena was separated from several samples from the old mine dumps and analyzed for Pb isotopic composition by GEOSPEC Consultants Limited, Canada, as described by Thorpe and others (1984). Galena from the Copps Mine has a very radiogenic Pb isotopic composition with extremely high $^{207}\text{Pb}/^{204}\text{Pb}$, while having low $^{208}\text{Pb}/^{204}\text{Pb}$ relative to $^{206}\text{Pb}/^{204}\text{Pb}$: $^{206}\text{Pb}/^{204}\text{Pb}=18.712$, $^{207}\text{Pb}/^{204}\text{Pb}=16.413$, and $^{208}\text{Pb}/^{204}\text{Pb}=37.024$. The Copps Mine galenas are more radiogenic than both the Archean and Early Proterozoic veins in the Ishpeming greenstone belt (Bornhorst and others, in review), as well as the Early Proterozoic volcanogenic massive sulfide deposits in northern Wisconsin (Afifi and others, 1983). If it is assumed that the Copps Mine Pb was derived from a source that shared the general Pb evolution of the Marquette-Ishpeming galenas, calculated slopes are 0.2970 to 0.3073 when the Copps Mine data are extrapolated to Ropes Mine (gold-bearing) and Holyoke quartz-carbonate (gold-barren) galenas, respectively. At an assumed initial source age of 2700 Ma, a two-stage age of 1700 to 1800 Ma is indicated for the Copps galena.

If the source was isotopically reset at 2600, the calculated two-stage age for Copps galena is about 1835 to 1935 Ma. The very radiogenic Pb isotopic composition seems to clearly indicate that a large component of Pb has been recycled from much older upper crustal sources, and could be explained by recycling of Pb from old gneiss such as the 3560 Ma Watersmeet Dome (Sims and others, 1984).

The Copps Mine two-stage age of 1700 to 1935 Ma is contemporaneous with the age of several important geologic events in the Great Lakes region. Volcanism and plutonism of the Wisconsin magmatic terranes of the Penokean orogen occurred between 1760 and 1889 Ma (Sims and others, 1989). Deformation related to the arc-continent collision along the Niagara suture to the south occurred at about 1860 Ma (Sims and others, 1989). Ductile deformation associated with the Mountain shear in northeastern Wisconsin occurred about 1815 Ma (Sims and others, 1990). Post-tectonic granite occurs south of the Ishpeming greenstone belt at about 1733 Ma (Schulz and others, 1988). The large uncertainty in the galena two-stage ages for the Copps Mine indicates that vein formation could be compatible with any of these events or with other unmentioned events. We favor interpreting the vein mineralization as contemporaneous with suturing.

This study would not have been possible without funds for Pb isotope analysis provided by Western Mining Corporation (USA).

REFERENCES CITED

- Afifi, A., Doe, B.R., Sims, P.K., and Delevaux, M.H., 1984, U-Th-Pb isotope chronology of sulfide ores and rocks in the Early Proterozoic metavolcanic belt of northern Wisconsin: *Econ. Geol.*, v. 79, p. 338-353.
- LaBerge, G.L. 1992, The Early Proterozoic Emperor Volcanic Complex: Implications for the geology of the eastern Gogebic District, northern Michigan: *Proceedings 38th Ann. Instit. on Lake Superior Geol.*, v. 38, p. 53-55.
- Bornhorst, T.J., Thorpe, R.I., and Johnson, R.C., in review, Lead isotope study of vein mineralization in the Archean Ishpeming greenstone belt, Michigan: *Econ. Geol.*
- Schulz, K.J., Sims, R.K., and Peterman, Z.E., 1988, A post-tectonic rare-metal-rich granite in the southern complex, Upper Peninsula, Michigan: *Proceedings and Abstracts 34th Ann. Instit. on Lake Superior Geol.*, v. 34, p. 95-96.
- Sims, P.K., Klasner, J.S., and Peterman, Z.E., 1990, The Mountain shear zone, northeastern Wisconsin- A discrete deformation zone within the Early Proterozoic Penokean orogeny: *U.S. Geol. Survey Bull.* 1904-A, 15p.
- Sims, P.K., Peterman, Z.E., Prinz, W.C., and Benedict, F.C., 1984, Geology, geochemistry, and age of Archean and Early Proterozoic rocks in the Marenisco-Watersmeet area, northern Michigan: *U.S. Geol. Survey Prof. Paper* 1292-A, 41p.
- Sims, P.K., Van Schmus, W.R., Schulz, K.J., and Peterman, Z.E., 1989, Tectono-stratigraphic evolution of the Early Proterozoic Wisconsin magmatic terranes of the Penokean orogen; *Canadian Jour. of Earth Sci.*, v. 26, p.2145-2158.
- Thorpe, R.I., Guha, J., Franklin, J.M., and Loveridge, W.D., 1984, Use of the Superior Province lead isotope framework in interpreting mineralization stages in the Chibougamau District: *Canadian Instit. of Mining and Metallurgy Special Volume* 34, p. 496-516.
- Trent, V.A., 1973, Geologic map of the Marenisco and Wakefield NE quadrangles, Gogebic County, Michigan: *U.S. Geol. Survey Open-File Report*, scale 1:20,000.

PETROGRAPHIC EVALUATION OF ORE TEXTURES FROM
MANGANIFEROUS IRON FORMATION AND COPPER-OXIDE PORPHYRY
FOR IN SITU MINING POTENTIAL

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As part of its Advanced Mining Research program, the U.S. Bureau of Mines is conducting laboratory leaching experiments of drill core samples to develop in situ mining processes to selectively extract manganese and copper from their respective oxide deposits. In situ mining uses injection wells for pumping leach solution, which is selective for the target metal, into the ore body. The leach solution percolates through the natural permeable pathways within the mineralized zone and dissolves the desired metal. The metal-bearing leach solution is drawn to the surface via recovery wells. Attractive features of in situ mining compared to conventional mining methods are the relatively inexpensive extraction of the desired metal from small or low grade deposits, the increase in miner safety and minimal environmental impact.

In developing in situ mining technology, it is important to evaluate the combined effect of textures, mineral distribution, and mineral reactivity on the leachability of contained metal values using petrographic techniques. As part of the Bureau's in situ mining program, therefore, detailed petrographic studies on preleach and postleach Mn-rich and Cu-rich rock samples are being conducted using optical microscopy, scanning electron microscopy, microprobe analysis, transmission electron microscopy, and X-ray diffraction. Of particular interest in developing in situ leach mining processes, is the effect of mineral and rock textures on target mineral reactivity. Differences between the mechanisms of dissolution between target-metal-bearing minerals that are predominantly fracture-hosted, such as copper oxides in an oxide porphyry Cu deposit, and dissolution of predominantly matrix-hosted

manganese oxides, in a manganiferous iron-formation deposit have been investigated. Permeability changes that result from leaching of a mineralized rock sample have also been studied. Increased porosity and permeability occur when the target mineral has been dissolved, however, a decrease in porosity and permeability may be caused by secondary mineral precipitation, mobilization and packing by insoluble particles, or mineral swelling. Petrographic study of preleach and postleach rock samples enables one to determine and potentially optimize the leachability of a particular ore by identifying causes and effects in the fluid/rock system.

OCCURRENCE AND CARBON ISOTOPIC COMPOSITION OF SOME WISCONSIN GRAPHITES

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Graphitic schists are a common rock type within the Archean/early Proterozoic terranes of central and northwestern Wisconsin and the intervening early Proterozoic island-arc terrane of northern Wisconsin. These rocks are rarely exposed, but have been intersected in numerous mineral exploration drill holes. Graphite typically occurs within finely laminated siliceous to semipelitic metasedimentary rocks interbedded with felsic to mafic metavolcanic rocks. Low-grade sulfide mineralization (mainly pyrite-pyrrhotite) is commonly associated with graphitic zones and is typically concentrated in graphite-rich horizons. Samples analyzed in this reconnaissance study are from 6 drill cores from Clark, Jackson, and Wood Counties in central Wisconsin. Analysed samples contain up to 40% graphite. There are thin layers (< 1mm thick) of nearly pure graphite within some of the samples.

Strauss (1986) reported $^{13}\text{C}/^{12}\text{C}$ ratios with $\delta^{13}\text{C}$ ranging from -47 to -15 per mil from late Archean graphite and from -30 to -17 per mil for early Proterozoic graphite in carbonaceous metasedimentary rocks from the Churchill and Superior Provinces of the Canadian Shield. Values obtained in the present study range from -28 to -16 per mil. E.C. Perry of Northern Illinois University has obtained values ranging from -25 to -19 per mil from graphitic horizons associated with iron formation in the Butternut area of northwestern Wisconsin (E.C. Perry, personal commun., 1993). Ratios determined in this study and that of Perry fall within the field of overlap of Strauss (1986) and, therefore, do not distinguish Archean versus early Proterozoic ages of formation of the graphitic rocks. The number of analyzed samples and their geographic distribution is limited, however, and future success with this method for age discrimination in Wisconsin cannot be ruled out.

All of the values determined in this study, with the exception of a -16.6 value from a Jackson County sample are consistent with an origin as metamorphosed organic matter. The -16.6 value suggests remobilization of carbon and mixing with other reservoirs, possibly precipitated carbon from carbonates mixing with organic carbon.

Reference:

Strauss, H., 1986, Carbon and sulfur isotopes in Precambrian sediments from the Canadian Shield: *Geochimica et Cosmochimica Acta*, vol. 50, p. 2653-2662.

BRECCIATED AND SILICIFIED FELSIC VOLCANIC ROCKS OF LATE-OR POST-PENOKEAN AGE IN CENTRAL WISCONSIN

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Wisconsin Geological Survey field parties working in central Wisconsin from 1916 to 1919 reported scattered outcrops of "quartzite" in Clark, Jackson, and Wood Counties. Recent field and petrographic study indicates that these rocks are actually highly brecciated and extensively silicified felsic volcanic rocks that are undeformed and appear to be unmetamorphosed. The breccias occur in a terrane that consists mainly of Archean gneiss and syn- to post-kinematic tonalites to granites emplaced during the Penokean orogeny at 1820-1890 Ma. Volcanic rocks similar to the fragments in the breccias have not been found elsewhere in the area. Preservation of the breccias as isolated erosional remnants is attributed to their high degree of silicification.

The breccias are typically composed of less than 20% angular fragments of equigranular to porphyritic felsic volcanic rock in a matrix of white to pink vein quartz. White quartz is most common, but color may range to green and red depending on iron content and degree of weathering. The porphyritic fragments contain quartz phenocrysts and, less commonly, quartz and microcline phenocrysts, suggesting that they are rhyolitic. Spherulitic quartz is present in one fragment. A few of the fragments are faintly banded tuffs and others were fragmental volcanic rocks prior to brecciation and silicification. There are fragments of undeformed granite within one of the breccias. Neither the volcanic fragments nor the more stress-sensitive quartz veins exhibit evidence of penetrative deformation. Minor to moderate undulatory extinction of quartz is displayed in some samples.

Open vugs lined with epitaxial growths of quartz in some of the breccias suggest shallow depths of formation. The breccias probably formed in or proximal to volcanic vents, and may represent explosion breccias produced by phreatic eruptions and later cemented by quartz deposited from hydrothermal solutions.

The volcanic fragments in the breccias have not been dated. The outcrops of breccia in Clark and Jackson Counties are in an area where all but the youngest of the Penokean intrusive rocks are deformed and metamorphosed. The absence of any evidence of penetrative deformation in the breccias suggests that they can be no older than the final stages of the Penokean orogeny. These rocks are notable because they represent a previously unrecognized volcanic sequence in this area. It is possible that they: a) belong to the 1760 Ma magmatic event that produced numerous rhyolites and granites in south-central Wisconsin and scattered granites in northern Wisconsin, b) are related to the enigmatic 1630 Ma thermal event recorded by Rb/Sr systematics throughout the region, or c) are associated with the 1500 Ma Wolf River batholith to the northeast.

REACTIVATED ARCHEAN STRUCTURES, PROTEROZOIC STRATIGRAPHY AND MINERAL DEPOSITS; WESTERN UPPER MICHIGAN

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Basement structures related to the late Archean continental collision along the Great Lakes Tectonic Zone appear to have been reactivated during the Proterozoic. Evidence for this reactivation includes: isopach and facies variation in Proterozoic stratigraphy, location of intrusions and the formation of mineral deposits. The sequence of proposed events is:

- 1) Formation of fabrics trending east-west and northwest during the suturing of the Archean cratons at approximately 2.5 Ga.
- 2) Rifting and sedimentation associated with basins that were localized by these fabrics during the development of a passive margin prior to the Penokean Orogeny.
- 3) Folding and thrusting during collision associated with the Penokean Orogeny.

The Proterozoic basins in the Marquette, Gwinn and Republic areas formed parallel to the underlying Archean fabric and acted as hosts for the banded iron formations, Kona copper deposits and other base and precious metal occurrences. There is some indication that the areas in which these mineral deposits are most concentrated lie at the intersection of the east-west and northwest trends found in the basement. We propose that continued reactivation of these basement structures focussed the deep iron formation basins and acted as conduits for igneous intrusions and fluid flow associated with other mineral deposits, perhaps including Keweenawan copper and Mesozoic kimberlites.

THE KALLANDER CREEK VOLCANICS--A REMNANT OF A KEWEENAWAN CENTRAL VOLCANO CENTERED NEAR MELLEN, WISCONSIN

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The Kallander Creek Volcanics (KCV) is a sequence of basalt, andesite, and rhyolite that was erupted between about 1102 and 1108 Ma in the Lake Superior portion of the Midcontinent rift. It occurs in a belt more than 100 km long on the south limb of the rift in Wisconsin and Michigan. The belt disappears beneath younger cover on both east and west ends, so the true extent of the unit is not known. The Mellen complex, consisting of gabbroic rocks, granophyre, and granite, was intruded into the KCV at 1102 Ma.

We propose that the KCV is the partly eroded remnant of a central volcano, comparable in scale and composition to the younger Porcupine volcano centered about 75 km to the east. The Mellen complex represents the crystallized remains of a magma chamber that was intruded into the volcanic edifice late in its eruptive history.

Keweenaw volcanism in the Mellen area began with eruption of a 1.5-km-thick sequence of mostly high-Al flood basalts of the Siemens Creek Volcanics at about 1109 Ma (assuming approximate correlation of the Siemens Creek with the Osler Group on the north shore of Lake Superior). The basal flows are nearly everywhere pillowed as a result of eruption into a shallow lake; the remainder are subaerial flows. The Siemens Creek maintains approximately constant thickness across the Mellen area, except where it is intruded by the Mellen complex, indicating that the surface remained nearly featureless throughout the time of eruption.

The KCV overlies the Siemens Creek and records a change in eruptive style from the probable fissure-fed flood basalt volcanism of the Siemens Creek to formation of a broad central volcano. The KCV ranges from 2 to 4 km in thickness, but its original thickness is obscured by intrusion of the Mellen complex, by faulting, and by erosion, some of which probably occurred prior to eruption of the overlying Portage Lake Volcanics. A rhyolite near the middle (2.5 km above the base) of the KCV has a U-Pb zircon age of 1107 ± 2 Ma.

The Mellen complex was intruded into the KCV late in the formation of the volcano; the complex includes the Mineral Lake intrusion and Mellen granite. A granophyre in the Mineral Lake intrusion has a U-Pb zircon age of 1102 ± 2 Ma. The Mellen granite, which intruded and brecciated gabbro of the Mineral Lake intrusion, has an indistinguishable age of 1102 ± 2 Ma. The Mellen granite cuts all preserved parts of the KCV and, therefore, sets a minimum age for those rocks.

The presence of the volcano centered near Mellen affected the distribution and lithology of younger rocks. The overlying Portage Lake Volcanics, mostly high-Al flood basalts with minor rhyolite, is typically about 5 km thick, but pinches out near Mellen, in part because of the volcano's positive topographic expression. In the immediate Mellen area, the Portage Lake consists mostly of a single eruptive unit of rhyolite. The base of the Portage Lake east of Mellen can be assigned an age of about 1096 Ma, the age of the Copper City flow on the Keweenaw Peninsula. Abundant exploration drilling and outcrop data allow tracing of the Copper City horizon from the peninsula to about the east edge of the area shown in Figure 1. Because the upper parts of the KCV can be no younger than 1102 Ma, there is about a 6-m.y. hiatus between the KCV and Portage Lake Volcanics. That hiatus may represent a period of erosion during which part of the KCV volcano was destroyed, faulting between the two units, or some combination of the two.

The Copper Harbor Conglomerate also pinches out near Mellen, as does the overlying Nonesuch Shale. The Nonesuch becomes interbedded with red sandstone and

conglomerate near Mellen, apparently reflecting a local sediment source and alternating lacustrine and fluvial deposition. Finally, the Freda Sandstone is dominated by coarse sandstone and conglomerate near Mellen, where it lies unconformably on the Mellen complex and KCV; at least one conglomerate bed extends as much as 20 km to the east. Closer to Mellen, red and greenish conglomerate and breccia are locally predominant. Unsorted angular clasts of basalt and lesser gabbro in places indicate that local relief on the eroding volcano was still providing a sediment source well into the Freda depositional interval.

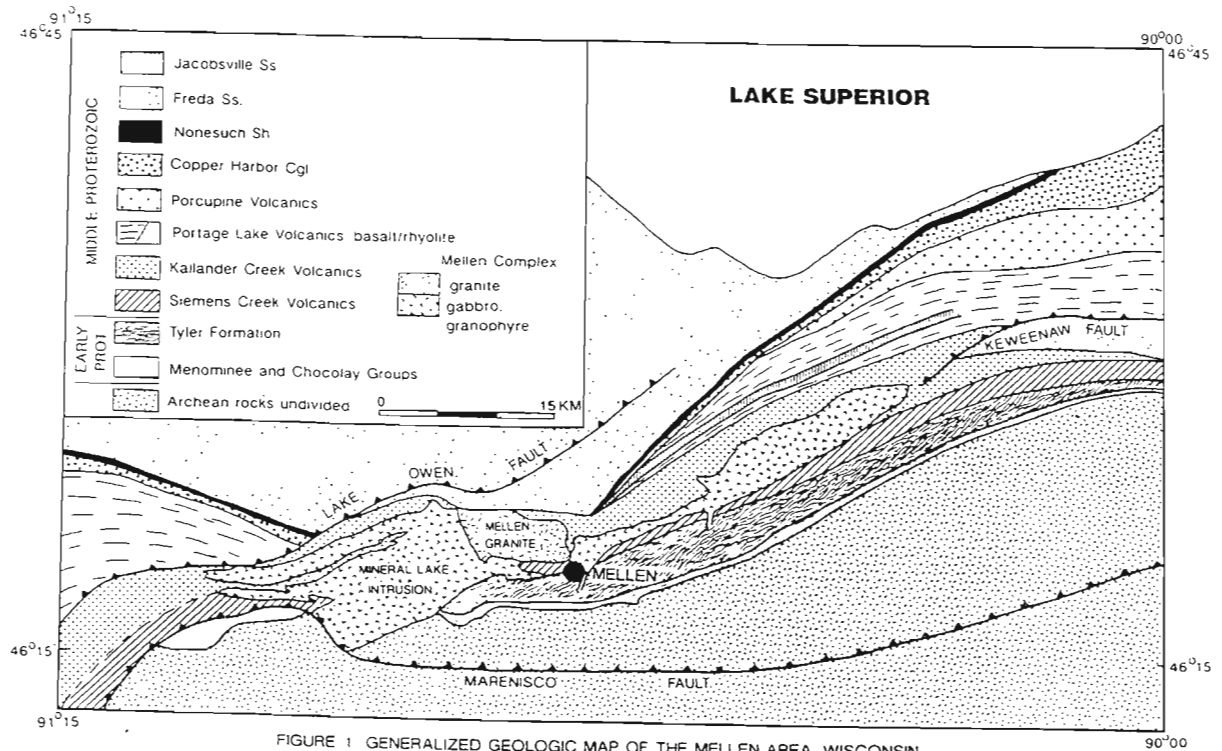


FIGURE 1. GENERALIZED GEOLOGIC MAP OF THE MELLEN AREA, WISCONSIN

AN ARCHEAN UNCONFORMITY IN THE VIZIEN GREENSTONE BELT, UNGAVA PENINSULA, QUEBEC

by

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Reconnaissance mapping of a 100 x 400 km transect across the Ungava Peninsula in northeastern Superior Province has revealed a well-preserved unconformity between 2940 Ma tonalitic basement with mafic dykes and a younger (<2718 Ma), middle amphibolite facies metasedimentary-metavolcanic sequence within the Vizion greenstone belt surrounded by high-grade metamorphic and plutonic rocks of the Minto block. The unconformity-based package is the youngest of at least three distinct supracrustal assemblages juxtaposed by faults. A regolith of quartz-muscovite grit developed in the tonalite beneath the unconformity is depositionally overlain by polymictic conglomerate, quartz pebble conglomerate and grit, greywacke, and mafic-ultramafic komatiitic volcanics including structurally emplaced units. Weathering of the tonalite to form grit involved breakdown of plagioclase, increased SiO_2 , CIA number, and $\text{Fe}^3/\text{Fe}_{\text{total}}$, and decreased CaO, Na_2O , Sr, and Na/K ratio. The Vizion unconformable package is similar in age but not in lithology or structural setting to Timiskaming-type assemblages and bears a strong resemblance to the Steep Rock Group of Ontario. The presence of rock units spanning >200 Ma, and their unconformable relationship, support the lengthy complex history of crustal recycling in northeastern Superior Province evident from Nd isotopic studies.

GEOPHYSICAL STUDIES IN THE DULUTH AREA, NORTHEASTERN MINNESOTA

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Gravity and recently acquired high-resolution aeromagnetic data were used to supplement geologic mapping of the Duluth Complex at Duluth, Minnesota. The gravity data consisted of stations from earlier surveys that were spaced about 1.6 km apart (Chandler and Schaap, 1991), and stations along two detailed profiles that were acquired during this study. The aeromagnetic data in Minnesota were acquired as a part of the high-resolution aeromagnetic survey program of the Minnesota Geological Survey (Chandler, 1991) and consisted of data collected along north-south lines spaced 400 m apart at an altitude of 150 m. This study also used aeromagnetic data recently acquired over Lake Superior and northwestern Wisconsin by the Geological Survey of Canada and the U.S. Geological Survey, respectively, as part of the Great Lakes International Multidisciplinary Project on Crustal Evolution (Teskey and others, 1991). The high-quality gravity and aeromagnetic data sets, combined with the locally excellent outcrop control in the Duluth area, afford a unique opportunity to examine the geologic significance of anomaly signatures associated with the Duluth Complex, and to use this information to extend geologic mapping into more poorly exposed parts of the complex.

Derivative-enhanced gravity and aeromagnetic data reveal several important details regarding the structure of the complex. The layered series, which forms the lower part of the complex, is delineated sharply in the derivative data by a busy, moderate-amplitude magnetic signature, and a moderately positive gravity signature. The derivative data show that the basal contact of the layered series strikes generally north-south, but swings to form a convex-eastwards cusp near 47° N. Patterns in the derivative gravity and aeromagnetic data imply that the base of the layered series may swing to the northeast and truncate older intrusive units of the complex to the north. The upper part of the layered series, which includes the cyclic gabbro and upper contact zone (Miller, Green, and Chandler, field trip for this meeting), is associated with strongly positive gravity and magnetic anomalies in the derivative data, reflecting the oxide-rich character of these evolved mafic rocks. This belt of prominent gravity and magnetic signatures can be traced for at least 40 km northeast of Duluth. The strong gravity and magnetic signatures associated with the upper part of the layered series appear to overwhelm the anomaly expression of the anorthositic and granophyric rocks, which apparently form only a thin cap over the layered series. Lavas of the North Shore Volcanic Group, which form the roof of the Duluth Complex, are associated with a weak, slightly banded magnetic signature and a negative gravity signature in the derivative data. Diabasic intrusions into the lavas correspond to local maxima in the magnetic data, and large, strongly positive gravity and magnetic anomalies just offshore and northeast of Duluth strongly resemble the signatures that are associated with a large mass of diabasic and layered intrusive rocks that lies some 80 km northeast of Duluth (Chandler and others, 1991).

Preliminary model studies of the gravity and magnetic data indicate that the basal contact of the Duluth Complex dips somewhat more steeply than the lavas into which the complex supposedly was emplaced. This geometry differs from the sill-like geometry that is commonly envisioned for this part of the Duluth Complex, and implies that the complex cuts across the lavas, possibly along fault-related contacts.

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More recent work was supported by the Legislature under the Minerals Diversification Program administered by the Minerals Coordinating Committee.

REFERENCES CITED

- Chandler, V.W., 1991, Aeromagnetic anomaly map of Minnesota: Minnesota Geological Survey State Map Series S-17, scale 1:500,000.
- Chandler, V.W., Miller, J.D., and Venske, E.A., 1991, Description of map sheets for the central Duluth Complex shallow drilling project: Minnesota Geological Survey Open File Report 91-4, 4 p., 1 sheet, scale 1:100,000.
- Chandler, V.W., and Schaap, B.D., 1991, Bouguer gravity anomaly map of Minnesota: Minnesota Geological Survey State Map Series Map S-16, scale 1:500,000.
- Teskey, D.J., Thomas, M.D., Gibb, R.A., Dods, S.D., Kucks, R.P., Chandler, V.W., Fadaie, K., and Phillips, J.D., 1991, High resolution aeromagnetic survey of Lake Superior: EOS, Transactions American Geophysical Union, v. 72, p. 81, 85-86.

IMPLICATIONS OF TOURMALINE-RICH ROCKS IN THE NORTH RANGE GROUP OF THE CUYUNA IRON RANGE, EAST-CENTRAL MINNESOTA

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The Cuyuna Iron Range in east-central Minnesota was an important producer of iron and manganiferous iron ore from the early 1900s until closure in 1984. Much of the historical production was from the North Range, where nearly half of the manganese resource identified in the United States is contained in the Trommald Formation. The Trommald Formation is a sequence of iron-rich strata sandwiched between two clastic units, the Mahnomen Formation below and the Rabbit Lake Formation above. The three formations collectively define the North Range Group.

Previous studies concluded that the manganese-rich parts of the Trommald were sedimentary in origin, and that they form discrete beds interlayered between thick-bedded, granular strata having shallow-water depositional attributes and thin-bedded, nongranular strata having deeper water attributes. However, a recent reevaluation of drill core and mine samples from the northwestern part of the North Range has identified a variety of minerals -- including rhodonite, rhodochrosite, hyalophane, barite, aegirine, and tourmaline -- indicative of submarine-exhalative processes. The Trommald Formation has many of the features that J. Bonatti, in 1975, attributed to hydrothermal ferromanganese deposits found in sediment-hosted, submarine exhalative environments. Tourmaline-rich zones in the North Range Group occur in metasedimentary rocks toward the base of the Trommald and top of the underlying Mahnomen Formation, and within an argillaceous unit in the upper part of the Trommald Formation. Tourmaline has also been described by R.G.Schmidt in 1964 from the basal part of the Rabbit Lake Formation. In these occurrences, tourmaline accounts for <1 to ~18 volume percent of beds of shale and quartz-rich sandstone that have undergone greenschist facies metamorphism. The tourmaline-rich strata are internally layered and exhibit graded bedding. The formation of tourmaline requires elevated boron values that most likely were fluxed into the depositional system by hydrothermal fluids flowing along just below the sediment- or rock-water interface. Tourmaline formed where the solutions encountered favorable bulk-sediment or bulk-rock conditions, and especially where appreciable alumina was present in the host rocks. Consequently tourmaline occurs in the clastic parts of the North Range Group, but is generally lacking in iron-rich strata where only minor amounts of alumina are found.

Tourmaline-rich metasedimentary rocks are associated with stratabound polymetallic sulfides deposits at Rum Jungle, Northern Territory, Australia; Elizabeth

Canada (Figure 1). The compositions of tourmaline grains from these localities are broadly similar to those of the North Range Group and especially to those found in the host rocks associated with the Sullivan ore body (Figure 2).

D.E. Large in 1980 and J.A. Briskey in 1980 have proposed an ore-deposit model where ferromanganese deposits of submarine exhalative origin form a rim that caps and surrounds sedimentary-hosted sulfide deposits. If applicable, this model implies that the Trommald Formation in the northwestern part of the North Range is the outer part of such a hydrothermal system; the inner sulfide-rich part is yet to be found.

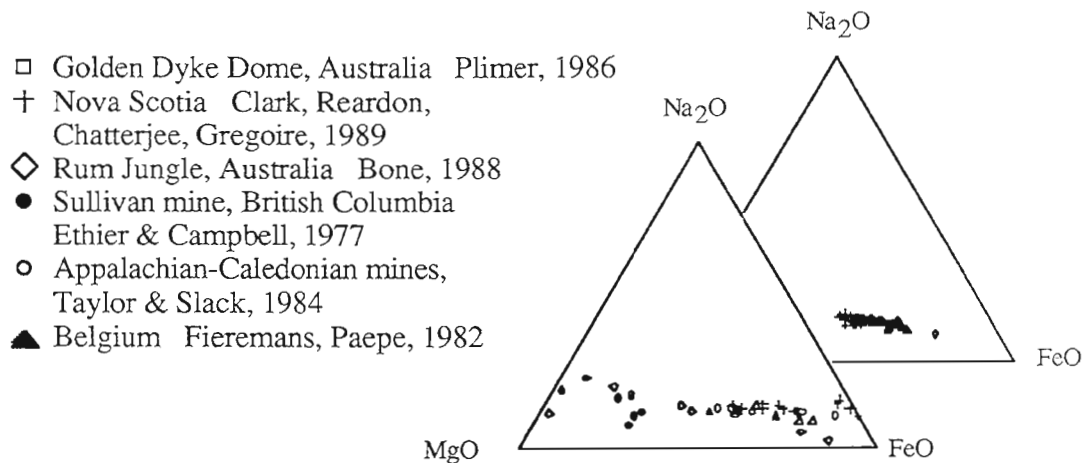


Figure 1. Compositions of tourmalines related to massive sulfide deposits, from the literature, are plotted on left-hand triangle. Tourmaline compositions from Cuyuna samples analyzed for this study are on right-hand triangle.

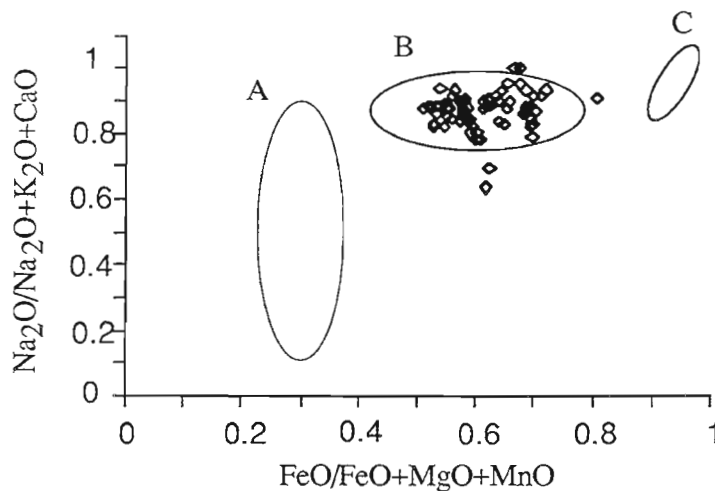


Figure 2. Tourmaline compositions from Cuyuna compared to compositions from Sullivan in terms of oxide ratios. A-Sullivan ore body; B-host rocks; C-nearby igneous intrusion (modified from Ethier and Campbell, 1977).

OUTCROP OFFSETS AND MICROSCOPIC KINEMATIC INDICATORS IN A PROTEROZOIC MAFIC DIKE-STRIKE SLIP FAULT ARRAY, BLACK RIVER FALLS, WISCONSIN

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Below the Lake Arbutus dam along the Black River is an exposure of the Hatfield gneiss and amphibolites (~2.8 Ga) in which F2 folds and L1 lineations plunge steeply to the southeast (Maas and others, 1980; Sims, 1990). Cross-cutting the gneisses is a closely spaced array of strike-slip faults and mafic dikes that strike ~E-W within an area of about 1 square mile (Fig. 1). The mafic dikes contain Rb-Sr isotopic ratios that suggest a metamorphic resetting at ~2.0 Ga (DuBois, 1975); we interpret the ages and deformation of the dikes to be related to the Penokean orogen. We have differentiated 3 types of structures: strike-slip faults (6), mafic dikes (5), and fault-dike pairs (6). The fault-dike combinations contain mafic dike material that is along a fault boundary and both the fault cataclasites and dike material are foliated and sheared; faulting and dike emplacement were contemporaneous events. This outcrop is unique in that fault offsets can be measured and compared with the sense of microscopic kinematic shear (Table 1). We have observed examples where the outcrop fault offset (dextral) is opposite the sense of kinematic shear (sinistral) observed in thin section, or where both dextral and sinistral foliation offsets are preserved along strike of a given fault. Occasionally, both dextral and sinistral kinematic indicators were found in the same thin section.

The seventeen fault-dike structures observed here have a variety of lengths and widths (2 mm-1 m). Structures with dextral and sinistral offsets are equal in number (5), 2 faults have both dextral and sinistral offsets along strike, and 5 structures did not cross-cut country rock foliations such that an offset could be determined. The total amount of strike-slip offset was 521 cm, of which 253 cm was dextral and 268 cm was sinistral motion. Twelve of the 16 structures contained kinematic indicators that we could interpret: dextral shear (4), sinistral shear (3), and both (5). Comparing outcrop offsets and kinematic shear senses where both were present (8 sites), only 2 structures preserved complimentary kinematics (structures 1 & 2; Table 1). Fault offset equity is not preserved in this outcrop at any scale and the development of fault zone rocks and the emplacement of mafic magmas was coeval and very complex.

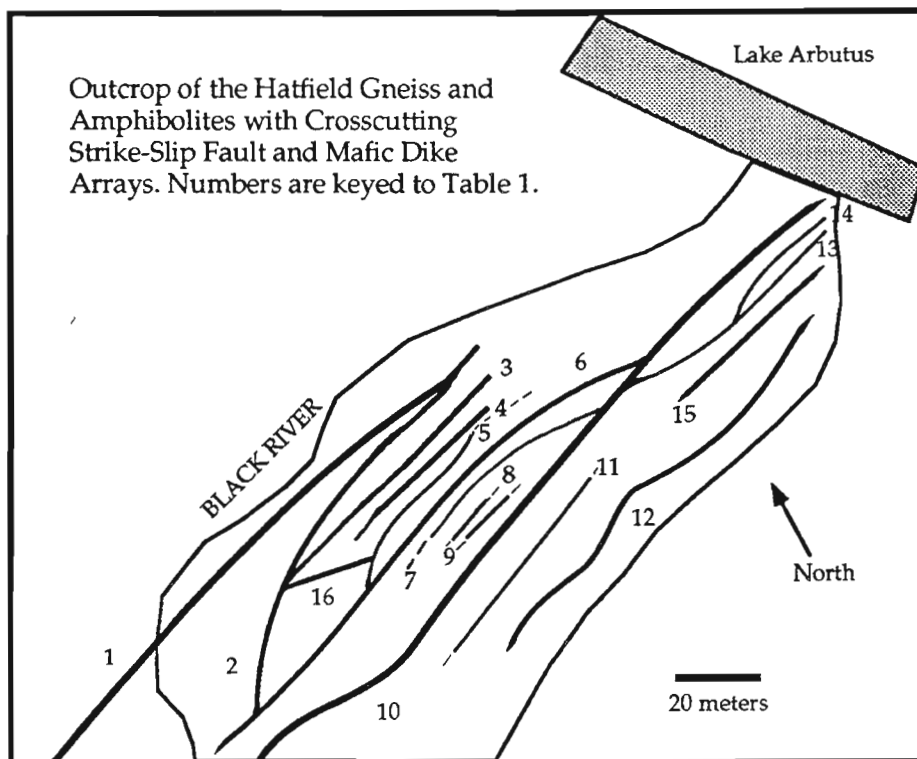
References

- DuBois, James F., 1975, Archean gneiss in the Lake Arbutus Aarea, Jackson county, west-central Wisconsin: M.S. thesis, University of Kansas, 69 p.
- Maas, R.S., Medaris, L.G., and Van Schmus, W.R., 1980, Penokean deformation in central Wisconsin: in Morey, G.B. and Hanson, G.N. (Eds.), *Selected Studies of Archean Gneisses and Lower Proterozoic Rocks, Southern Canadian Shield*, Geological Society of America Special Paper 182, p. 147-158.
- Sims, P.K., Geologic map of Precambrian rocks of Neillsville-Stevens Point area, central Wisconsin: U.S. Geological Survey Map I-1926 (1:100,000).

TABLE 1: Compilation of Outcrop and Thin Section Kinematic Indicators for Faults and Fault-Dike pairs, Black River Falls, WI.

Fault	Structure	Outcrop Offset (RL or LL)	Thin Section Kinematics	
			Offset	Type
1	Dike	RL	RL	S-C
2	Fault-Dike	RL,LL	RL,LL	S-C
2-3	Fault-Dike	?	RL	S-C
3	Dike	RL,LL*	RL	S-C, porphyroclasts
4	Dike	RL	---	---
5	Fault	LL	---	---
6	Fault-Dike	LL	RL,LL	S-C, porphyroclasts
7	Fault	RL	RL,LL	S-C
8	Fault	LL	---	---
9	Fault	LL	---	---
10	Fault-Dike	RL**	RL,LL	S-C, porphyroclasts
11	Fault	RL	LL	S-C, crenulations
12	Dike	?	LL	S-C
13	Fault	LL	RL,LL	S-C, crenulations, porphyroclasts
14	Fault-Dike	?	LL	S-C
15	Fault-Dike	?	---	Foliation, no offset
16	Dike	?	RL	S-C

[Key: RL=dextral offset, LL=sinistral offset. *-LL offset with RL fault drag; **-RL offset with LL fault drag].



CENTRAL MINNESOTA DRILL CORE LOGGING AND ASSAY

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This current work includes the new logging and assaying of existing DNR Drill Core Library samples. The examination of historical information has been necessary to implement these activities and to enhance their significance. A total of about 3900 drill sample data entries exist from the Region 3 area of Central Minnesota. These represent samples from approximately 2500 drill holes. Most of these holes were originally drilled in the search for iron and manganese in the Cuyuna Iron Range area during the first half of this century.

Samples from a total of 450 drill holes will be logged for this project, and approximately 650 samples will be analyzed. Many of these drill holes have not previously been included on the DNR Drill Core Library list. The historical information search has filled most previous data voids of drill holes currently on the Core Library List. The DNR Minerals Management Information Services will soon incorporate this data into a revised DNR Drill Core listing.

Of the lithologies encountered, the iron formation and associated rocks are typically deformed (brittle and brittle-ductile deformation), metamorphosed (low grade), altered, and recrystallized. Other rocks include gneiss, Keweenawan rift material, and schists that may represent the continuation of the Wisconsin Volcanic Massive Sulfide Belt. Evidence for the latter is the occurrence of coarse fragmental (volcanic?) rocks, brecciated siliceous marble and other chemical sediment, and dark biotite-chlorite alteration. The sulfide rocks of Glen Township may also be of this extension.

The rocks of the area also underwent a period(s) of pre-Pleistocene weathering before being glacially scoured. These effects have been superimposed on the original rock types. Weathering effects include limonitic, red hematitic, and goethitic alteration, although some goethitic alteration may be hydrothermal in nature. Local kaolinitic claystones from weathering may also occur (DDH 18226). From weathering, bauxitic (DDH 18400) and solution collapse (karst filling?) breccia (S1042, 18218, 18230) textures are locally developed. Vuggy (typically goethitic) portions may result from surficial weathering, although some may be sinter or hydrothermal related (DDH's S1044, S1053, S364, S1053, S1046, S1047, 18146, S361, 18600, 18400, 18131 and 18218).

Altered metagabbro occurs in DDH's 18135, 18144, 18145, BM-3 (fragmental??), AB-9, 86(?), BM-6(?), N-2, DL-4(?), DL-5(?), S257 and 18228.

Mafic metavolcanics may occur in DDH's 18138, 18230(?), 52, PA-4B-3(?), 16, 86(?), BM-6(?), 18134, 18137, DL-4(?), DL-5(?), AB-28, S261, 101, JW-1, and KRCH-8(?).

Magnetite-silicate iron formation (some with chert) occurs in numerous cores including DDH's 306 (15464), 307 (calcareous), 308 (calcareous), 18138, 18226, 18132, 18427, 18435, 18146, S1060, 18218, 18230 (no magnetite), 18223 (no magnetite), S1006, S12, S22 and S1060; with DDH's S1060, 18138, 18132, 18218, 18427, 18435, 18146(?), 18230, 18223, S1060 and S1006 having veining with pyrite.

Ferruginous siltstones or phyllites occur in a number of cores, including DDH's 309, 18146, 18223, S1, S8, S1045, S1047, S1050, 18400, and S1053.

Exhalative sulfides may occur in DDH's 18138, 18132, 18427, 18435, 18600, 101, S140, S146, DRP-1, DRP-2, ML-42C, 16, G-4, G-1, 43, BM-10, 85, 58, BM-1, 86, 84, 208, 292 and 18223.

Quartzite and siliceous siltstone occur in DDH's S118, S124, S126, and S346.

Graphitic argillite-phyllite occurs in DDH's 306 (10963)(pyritic), S1045, S1047, and 18230(pyritic).

Rocks with a tuffaceous component may include DDH's 18226, 18427, 18146, 18230, S8, 18600, S1045(?), 101, 102, 193, 280, 52, G-2, 83, DL-1, DL-2, DL-3 and 18221.

Tourmalinites and tourmaline bearing rocks occur in DDH's 280, 61, 16, 208(?) and G-2(?).

Rocks with possible black schist related alteration include DDH's 16, 208, and DRP-1(?).

Lamprophyre related rocks occur in DDH's 52, 265-1/1, and 286-6/1.

Feldspathic porphyry occurs in DDH 18221.

Brecciation is notable in DDH's S1042, 18132, 18427, 18435, 18146, 18230, 18218, S1131, S1053, 18600, S43, BM-2, S21, 1019, 260 and S1060; with **hydrothermal brecciation** possibly occurring in DDH's S364, 18132, 18427, 18435, 18218, S1050, S1053, DRP-1, DRP-2, ML-55CA, 58 and 18146.

Veinlets with minor pyrite and iron oxides replacing pyrite(?) cubes occur in many drill core samples.

Logging is currently being done in a digital database format. The fields and current codes are listed elsewhere on the poster. An example of the database printouts are also shown.

Four hundred and fifty five samples were analyzed by Bondar-Clegg & Company Ltd. of Ottawa, Ontario. Ninety nine sample were analyzed using a 52 element package with the remaining samples analyzed using a 19 element package including gold. Samples were taken from drill core, cuttings and crushed core. Results are included elsewhere on the poster, with interesting highlights to follow.

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 TiO_2 also had higher K_2O and Al_2O_3 . DDH 310 had the highest **Cu** value (1622 ppm) which had an adjacent sample analyzed with the highest **Li** value (1145 ppm). The highest **As** value was 1362 ppm in DDH 280 (see tourmaline bearing rocks).

The data indicates that hydrothermal processes were active within the Region 3 area, and that there may be a high probability for undiscovered economic mineralization. Beside volcanic massive sulfide and sediment hosted massive sulfides, other applicable ore deposit models may include Olympic Dam type deposits, greenstone hosted gold, and five element vein type deposits.

ISOCON ANALYSIS OF CHEMICAL CHANGES IN MIGMATITES AND PALEOSOLS

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The isocon method of analyzing mass transfer was developed in Grant (1986) on the basis of Gresens' (1967) equations for metasomatic alteration. This simply involves plotting the chemical analysis of an altered rock against that of the original rock. Those species whose relative concentrations have not changed in the process define a straight line through the origin. This is called an isocon, and its slope gives the total change in mass in the metasomatism. The deviation of points above or below the isocon gives respectively the gain or loss of these species relative to the amounts in the original rock. The distance of a point from the origin depends on a scale factor, applied to the analyses of both original and altered rocks, used to prevent overlap. This has no effect on the conclusions except in clarity.

Here, we shall look at two applications of this method. First, in the closed-system model of migmatization an original rock (mesosome), is converted to a leucosome and selvage, perhaps through in-situ partial melting, with separation of the refractory selvage from the melt, which then crystallized to form the leucosome. Using data from Dougan (1979), on migmatites from New England, we first compare the selvage to the mesosome on an isocon diagram (figure 1). Mn, Ti, Mg and Fe form a linear array, and can be used to define an isocon. Thus, if the selvage were formed from the mesosome, Ca, Na, K, Al, Si and water were lost, in amounts given by their displacements from the isocon. In the closed system model, these would have formed the leucosome. So, next we compare this material (mesosome minus selvage) with the observed leucosome (figure 2). We find a superb fit: only water lies significantly off the isocon. This confirms the possibility of closed-system formation of the leucosome and selvage from the mesosome.

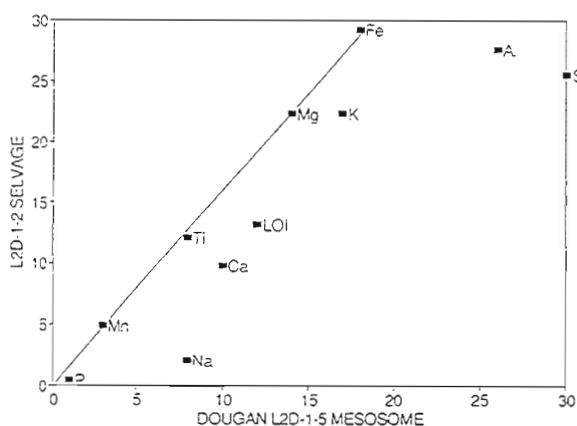


FIGURE 1

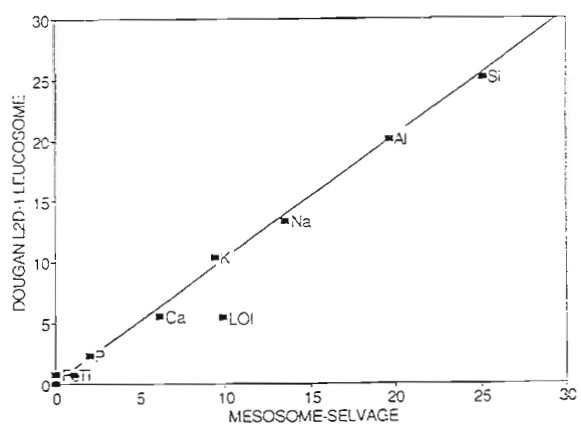


FIGURE 2

The second example comes from a metamorphosed zoned sequence in Finland, where quartz-sericite schist, chloritoid-kyanite-quartz schist and kyanite-quartz schist overly Archean granitoid basement. This sequence has been interpreted as the Hokkalampi paleosol (Jukka Marmo, personal communication, 1992). First we compare the Archean granitoid basement with the overlying quartz-sericite schists (figure 3), and note that there is a clear linear array, with Na and Ca lying far below the isocon. If the schist were formed from the granitoid basement, then Na and Ca were leached almost completely. Fe^{3+} was gained and Fe^{2+} lost,

but total iron (FeT) remained constant, indicating oxidation without loss of iron. Next, if the chloritoid-kyanite-quartz schist were formed from the quartz-sericite schist only Ti, Al, and Si would have been conserved, with loss of Mg, K, and most of the Fe^{3+} . Finally, in forming the most altered zone (kyanite-quartz schist) from the chloritoid schist even Fe^{2+} was leached, in the transition from a lateritic composition to a bauxitic one. The whole sequence can be viewed in the composite diagram of figure 4, where all three zones are compared to the parent granitoid. One can follow progressive loss of P, Mn, Na, Mg, K, Ca, Fe^{3+} , Fe^{2+} and total Fe from the quartz-sericite schist through the chloritoid schist to the kyanite schist. It is impressive that there is no significant change in the positions of Ti and Al, despite the extensive leaching of all else but silica in the most altered zone. This is surely clear proof of the immobility of Ti and Al in the process of formation of these zones, as is characteristic of lateritization.

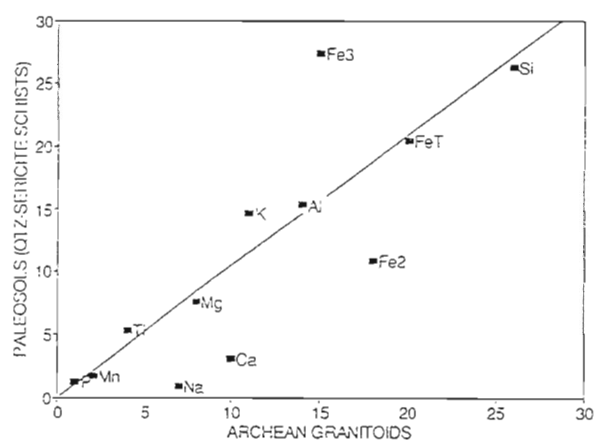


FIGURE 3

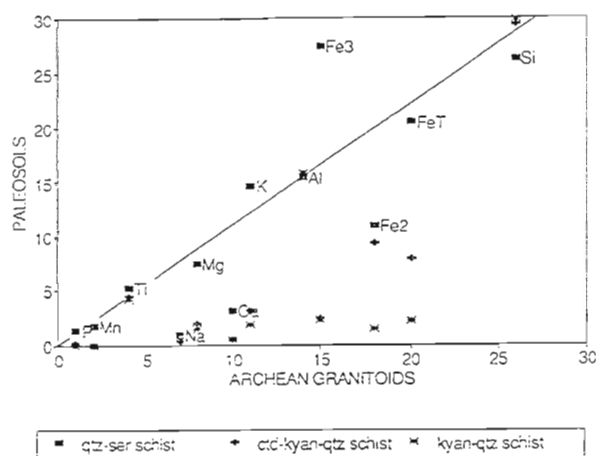


FIGURE 4

References:

- Dougan, T. W., 1979, Compositional and modal relationships and melting reactions in some migmatitic metapelites from New Hampshire and Maine. *Amer. J. Science*, v. 279, p. 897-935.
- Grant, J. A., 1986, The isocon diagram - a simple solution to Gresens' equation for metasomatic alteration. *Econ. Geology*, v. 81, p. 1976-1982.

STRATIGRAPHY AND VOLCANOLOGY OF THE NORTH SHORE VOLCANICS IN THE DULUTH QUADRANGLE

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Approximately 2445 m of volcanic strata occur above the Duluth Complex and beneath the Lester River (diabase) sill in the Duluth quadrangle. They include an unusually large proportion (37%) of felsic flows, consisting of five thick units of rhyolite and icelandite. The 600-m-thick Endion sill, the slightly transgressive and lensing Northland sheet, and two smaller diabase intrusions cut the volcanic rocks in this section (see stratigraphic diagram) (Oestrike, 1983; Jerde, 1991). Burial metamorphism has produced greenschist (epidote-chlorite +/- actinolite) and laumontite-prehnite-pumpellyite assemblages in the basalts (Schmidt, 1990; Schmidt and Green, 1992), and the lowest volcanic rocks are contact-metamorphosed by the underlying Duluth Complex to pyroxene-hornfels and hornblende-hornfels facies.

A basal sequence of intergranular basalt flows is preserved only locally in the roof of the Duluth Complex near Central High School. It is succeeded by the 130-m-thick City Hall icelandite, which underlies the Civic Center in downtown Duluth and appears to be a lava flow. The remaining 935 m of lavas beneath the Endion sill are all basalts. They include two distinctive porphyritic units, the 85-m Nettleton flow, which contains about 10% of small plagioclase phenocrysts, and the 125-m-thick Kenwood Avenue group, which consist about 40% of larger (5-10 mm) plagioclase phenocrysts. A large, massive, lensing ophitic basalt flow, up to 160 m thick, occurs in the UMD-Hartley Field area; it may have filled an erosional valley.

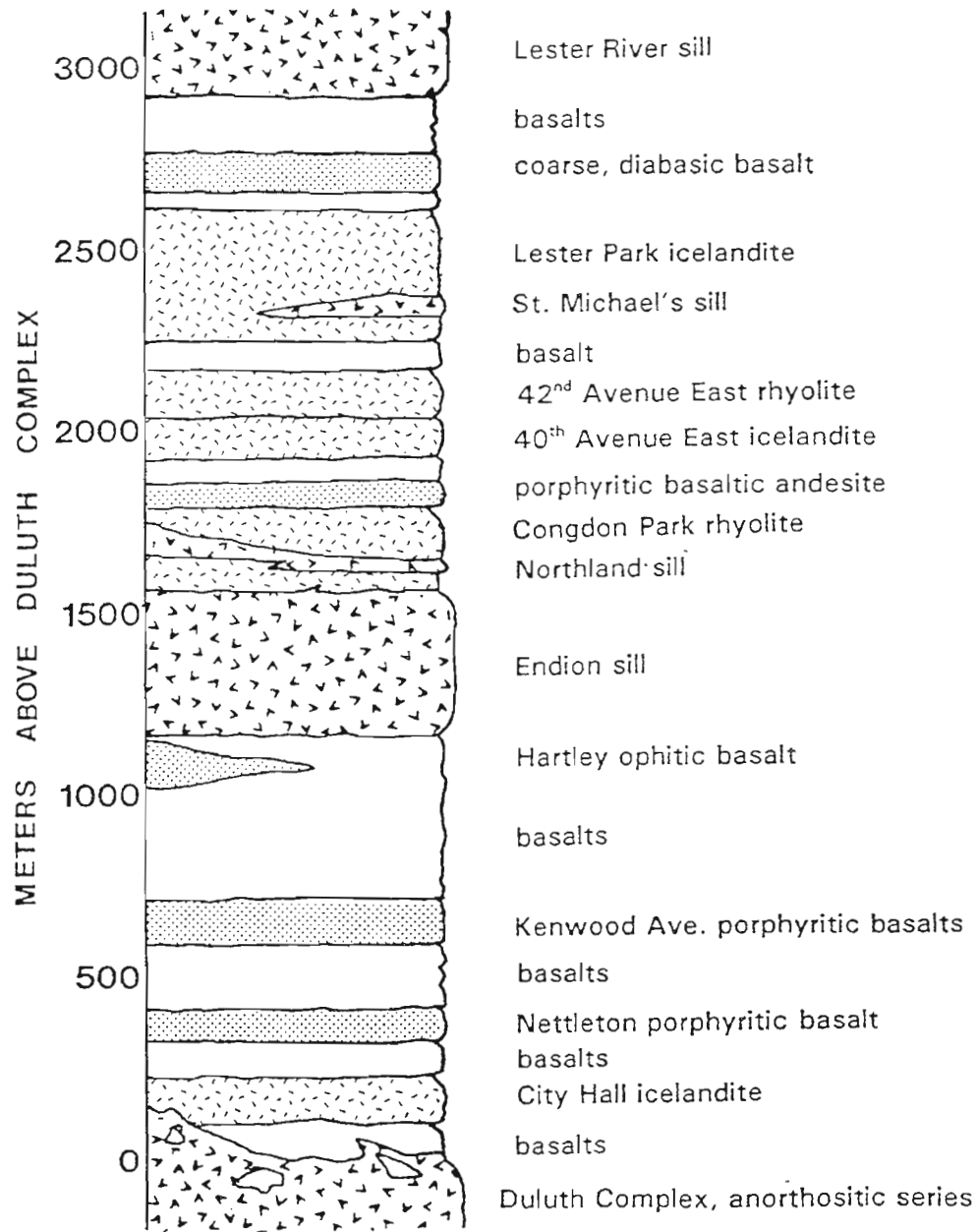
The sequence above the Endion sill starts with the 225-m Congdon Park rhyolite. Its base has been cut out or remelted by the underlying diabase, but its upper parts show it to be a rheoignimbrite - a pyroclastic flow deposit that welded and flowed after settling. It is overlain by porphyritic basaltic andesite, particularly well exposed above the Northland Country Club, followed by aphyric basalts and andesites. Overlying these is a large icelandite lava flow, the 40th Ave. East icelandite, which is followed by the 42nd Ave. East rhyolite. The lower half of this rhyolite is an unwelded or poorly-welded, pumice-rich ash-flow deposit, which is overlain without a structural break by a rheoignimbrite facies showing strong evidence of bulk flow after welding. A 75-m sequence of basalt flows overlies the flow-folded top of the rhyolite, and is in turn succeeded by the 300-m Lester Park icelandite, which is a lava flow. The final sequence of basalts below the Lester River sill includes a distinctive, 110-m-thick, coarse-grained, strongly altered, diabasic to ophitic flow.

The rhyolite and icelandite flows were remarkably fluid for such siliceous magmas. They show many flow features, crystalline interiors with tridymite, and a lack of autobreccia, and were probably erupted at unusually high temperatures (Green and Fitz, 1993).

References

- Green, J. C. and Fitz, T. J. III, 1993, Extensive felsic lavas and rheoignimbrites in the Keweenaw Midcontinent Rift plateau volcanics, Minnesota: petrographic and field recognition: *Jour. Volc. and Geotherm. Res.*, v. 54, p. 177-196
- Jerde, E. A., 1991, Geochemistry and petrology of hypabyssal rocks associated with the Midcontinent Rift, Minnesota: unpub. Ph.D. diss., Univ. of Calif. Los Angeles, 302 p.
- Motamedi, S., 1984, The Keweenaw lavas in the city of Duluth: unpub. M.S. thesis, Univ. of Minn (Duluth), 140 p.
- Oestrike, R. W., Jr., 1983, The Endion Sill, Duluth, Minnesota: mineralogy and petrology of a composite intrusion: unpub. M.S. thesis, Univ. of Illinois, Urbana, 141 p.
- Schmidt, S. Th., 1990, Alteration under conditions of burial metamorphism in the North Shore Volcanic Group, Minnesota - Mineralogical and geochemical zonation: *Heidelberger Geowissenschaftliche Abhandlungen*, Band 41, 309 p.

Schmidt, S. Th. and Green, J. C., 1992, Low grade metamorphism of the Keweenaw sequence in Minnesota and Michigan: Guidebook for Post-meeting field trip, 16-20 Sept., 1992, Internat. Geol. Correlation Programme, Project 294, Very Low Grade Metamorphism, 77 p.



ULTRAMAFIC LAMPROPHYRE DIKES WITH CARBONATITIC
AFFINITIES NEAR MARQUETTE, MICHIGAN; EVIDENCE IN SUPPORT OF
THE THIEL FAULT AND A TRANS-SUPERIOR TECTONIC ZONE.

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Ultramafic lamprophyres with carbonatitic affinities, a hitherto unrecognized rock type in the Lake Superior region of Northern Michigan, have been discovered on Little Presque Isle, an island in Lake Superior 7 miles northwest of the city of Marquette (Figure 1). A small swarm of ultramafic lamprophyre dikes, representing at least three separate emplacement events, cuts Archean tonalitic gneiss (2.6 b.y.) and is cut by Keweenawan diabase dikes (1.1 b.y.) on the northeast side of the island. Samples from four different lamprophyre dikes show a remarkable range in whole rock chemistry. One smaller dike is much higher in CaO and lower in SiO₂ than samples from any of the other dikes, whereas samples from a dike found on the western shore of the island are chemically quite similar to most samples taken from the major dikes within the study area (Figure 2). Some dike samples contain abundant calcitic ocelli and phlogopite phenocrysts. The fine-grained matrix is composed of Sr-rich calcite, phlogopite and abundant Fe-oxides. The Sr-rich calcite, low silica and potassium, and high REE content all indicate a mantle source for these rocks. The presence of calcite ocelli suggests liquid immiscibility and possible fractionation of a highly carbonaceous magma from a more silicious magma prior to emplacement (Ferguson, 1971). The Trans-Superior Tectonic Zone (Klasner *et al.*, 1982) extending from Ontario through Big Bay, Michigan, along the proposed Thiel Fault (Klasner *et al.*, 1979) has been linked to three mantle-derived intrusive complexes in southern Ontario: the Port Coldwell, Killala Lake, and Prairie Lake alkalic rock complexes. Radiometric dates of the Ontario complexes indicate emplacement around 1.05 b.y. (Sage, 1978). Both carbonatites and ultramafic lamprophyres have been tectonically linked to early rift stages (Rock, 1986). The tectonic and genetic affinities shared by the Ontario complexes and the Little Presque Isle dikes suggest coeval emplacement.

Additional occurrences were discovered on Middle Island Point and within the City of Marquette following initial field work on Little Presque Isle. Further study within the Marquette region will most certainly lead to the discovery of more lamprophyres, but radiometric dating and additional geochemical work will need to be done to fully assess the role of the lamprophyres in the tectonic evolution of the region.

References

- Ferguson, John and Currie, K.L., 1971, Evidence of Liquid Immiscibility in Alkaline Ultrabasic Rocks at Callander Bay, Ontario: *Journal of Petrology*, v. 12, p.561-585.
- Klasner, J.S., Cannon, W.F., and Van Schmus, W.R., 1982, The pre-Keweenaw tectonic history of southern Canadian Shield and its influence on formation of the Midcontinent Rift: *from Geology and Tectonics of the Lake Superior Basin* (Wold, R.J. and Hinze, W.J., eds.), 1982, Geological Society of America Memoir 156, p.27-46.
- Klasner, J.S., Wold, R.J., Hinze, W.J., Bacon, L.O., O'Hara, N.W., and Berkson, J.M., 1979, Bouguer gravity anomaly map of the northern Michigan-Lake Superior region, U.S. Geological Survey Geophysical Investigations Map GP-930, scale 1:1,000,000.
- Rock, N.M.S., 1986, The Nature and Origin of Ultramafic Lamprophyres: Alnoites and Allied Rocks: *Journal of Petrology*, v. 27, p.155-196.
- Sage, R.P., 1978, Diatremes and Shock Features in Precambrian rocks of the Slate Islands, northeastern Lake Superior: *Geological Society of America Bulletin*, v. 89, p.1529-1540.

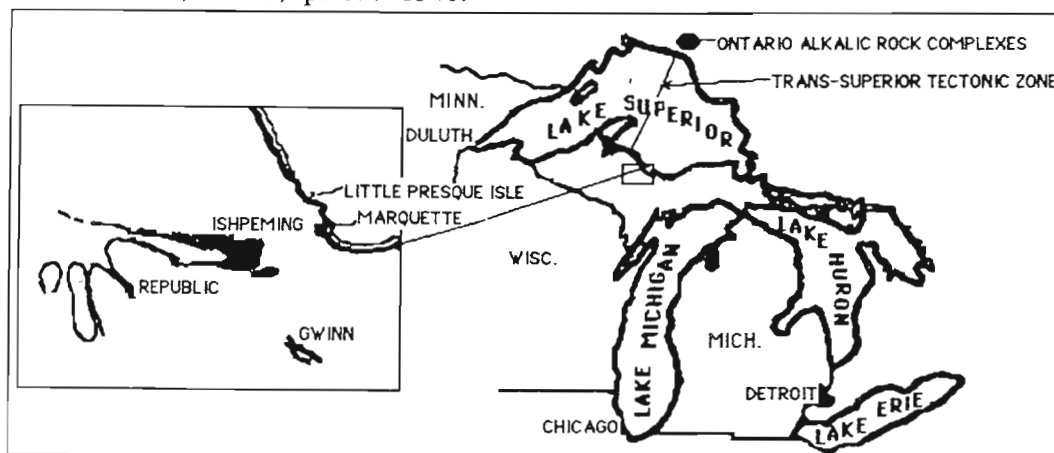


Figure 1. Little Presque Isle Location

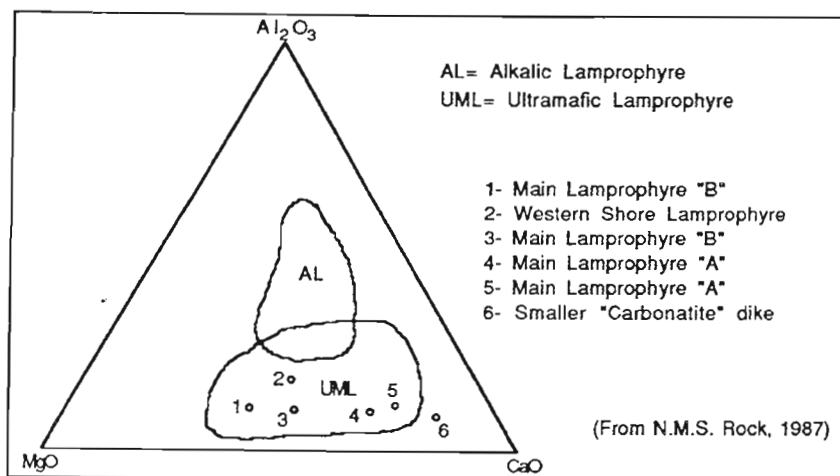


Figure 2. Little Presque Isle Ultramafic Lamprophyres

Computer Modeling in the Geosciences: Emphasis on Aeromagnetic Data-Techniques and Interpretations

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Aeromagnetic data for Minnesota indicates complex structural features. Contoured data maps are capable of only displaying general low-resolution information. Shaded relief maps portray higher resolution. Even higher resolution is possible using a raster-based GIS system. As equally important is the ability of the GIS display to enhance false color pattern recognition.

In 1988, the Minnesota Geologic Survey (MGS) in conjunction with the United States Geologic Survey (USGS) compiled a high resolution aeromagnetic database for all of Minnesota and the Lake Superior basin. This database has a gridded resolution of 0.045 square kilometers (12 acres). The data can be exported as ASCII values in an X,Y,Z or a Z-stream format. The X,Y,Z format can be imported to SURFER by GOLDEN GRAPHICS. SURFER provides good working contour maps and dropnet images, but it lacks the detail needed for fractal and Fourier analysis. It was discovered that the Z-stream format could be used, after proper manipulation of the raw data, in Eppl-7. Eppl-7 is a Geographic Information System (GIS) developed by the Minnesota Land Management Information Center (LMIC). After proper manipulation and some interpretation in EPPL-7, files are exported to IMPACT software by TARDIS Systems, Inc. for fractal and Fourier analysis. Fractal and Fourier analyses may illuminate the relationship of bedrock geology, tectonics, and glacial surface features including lakes and streams. Areas of study were Stearns and Wright Counties, Minnesota. These counties contain Superior and Des Moines glacial features.

Faults appear even more distinctly using the GIS method. Many other linear features not visible by the other techniques are easily seen, using false color imaging. Offsets are also enhanced.

Several types of features have appeared in GIS images which are not evident in contour or shaded relief maps. Some of these images appear to be plutons, others appear to be fracture or fault zones, others are as yet unexplained. The most dramatic feature in Central Minnesota is in the Lake Henry area (40 miles west of St. Cloud, 20 miles south of Sauk Centre). It appears to be a pluton approximately 10 miles in diameter. The aeromagnetic signature is almost perfectly circular. The signature has a "tail" which is also 10 miles wide and 60 miles long which dissipates with distance to the west.

A considerable number of similar features can be found throughout the region. Some of the features are elliptical rather than circular. Others appear to be distorted. Many of the "circular" patterns tend to have positive anomalies in the central regions with circumscribing negative anomalies. Others tend to have negative values in the center with positive values forming a "halo-pattern" around the central low.

Aeromagnetic features found in Central Minnesota will be shown and interactively discussed with the audience . Discussion will center on tectonic control from aeromagnetic evidence on surface glacial features.

KAOLIN RESOURCES IN MINNESOTA

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Minnesota has large kaolin resources located throughout the state. Currently, the resource is only being exploited in the south-central region of the state for use in bricks and portland cement. Past work in Minnesota has focused on defining the resources and occurrence of the various kaolin grades in the central region and specifically, in the areas of current mining. Current work is focused on an assessment of the occurrences of kaolin in northern Minnesota, using information and samples from the Minnesota Department of Natural Resources (MDNR) Drill Core Library located in Hibbing, MN.

Kaolin occurs in three varieties: 1) residual (primary) deposits formed during pre-Late Cretaceous weathering of various bedrock type; 2) reworked (secondary), sedimentary deposits formed from the residual deposits in a terrestrial fluvio-lacustrine environment; and 3) Late Cretaceous sediments which are organic-rich lacustrine, paludal, and marine in origin. All of these units were modified by Pleistocene glaciation and may be partially or completely removed from some areas of the state. Each of the three occurrences has distinct properties and are currently being mined in south-central Minnesota for use in the portland cement and brick industries.

The residual deposits in south-central Minnesota are currently used by the portland cement industry in Iowa. These deposits, weathered from the Morton Gneiss, are 10 to 75 m thick and consist of kaolinite (25% to 80%) and quartz (10% to 30%) as the major minerals with minor to trace amounts of illite, chlorite, feldspar, mica, and iron oxides present. As expected, the grade of the material decreases with depth. The kaolinite from these deposits is not well ordered and has a wide range of particle size. Residual deposits formed on other rock types, i.e., granites and felsic sediments, tend to have well-order kaolinite and a narrower range of particle sizes. Examples of these residual deposits are found formed on the Fort Ridgely Granite in south-central Minnesota.

Reworked, sedimentary deposits are currently used in the brick industry. These sediments overlie the residual deposits and consist of pisolitic kaolinite, shale, siltstone, and sandstone, with conglomerates. The sequence is typically fining upward from basal sandstones into shales, commonly capped by pisolitic kaolinite. This sequence may be repeated one or more times in an occurrence. Geologic mapping in south-central Minnesota has illustrated the fluvial nature of these deposits. The reworked package of sediments is commonly 2 to 10 m thick but may reach a thickness of 20+ m in some areas. Drill hole information indicates there are several of these occurrences in central and northern Minnesota, which are thought to be lacustrine sediments. The kaolinite in the reworked sediments is well ordered and has a narrow range of particle size in individual units. The shale, siltstone, and sandstones are dominantly composed of kaolinite and quartz with minor to trace illite and iron and titanium oxides. The pisolitic caps are kaolinitic with trace amounts of gibbsite and quartz. Iron oxides in the pisolitic caps can be minor to major in abundance and decrease with depth.

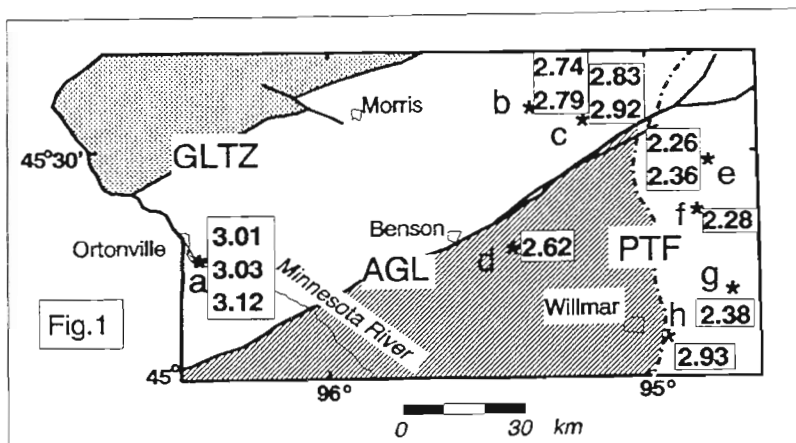
Late Cretaceous sediments, which overlie the residual and reworked kaolins, formed during the transgression of the Western Interior Seaway and are currently used in the brick industry. The sediments are composed of shales, siltstones, sandstones, and lignites, which occur in fining upward sequences. The Late Cretaceous sediment package ranges from 2 to 100 m in thickness. Typically, these are freshwater sediments, but marine examples occur in northern and western Minnesota. Mineralogically, they are composed of well-ordered kaolinite and quartz, with minor to trace illite, chlorite, gypsum, and carbonized material. Carbonate is present in many of the marine sediments but absent in the freshwater material. Many of the shale units are red firing ball clays and typically are 1 to 3 m thick. Drill hole information from northern Minnesota indicates there are thicker deposits of these ball clays preserved under the glacial overburden.

ND ISOTOPIC CONSTRAINTS ON THE PROVENANCE OF EARLY PROTEROZOIC SEDIMENTS AND THE LOCATIONS OF TECTONIC BOUNDARIES IN CENTRAL MINNESOTA

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Sm/Nd isotopic data from basement rocks in central Minnesota constrain the boundaries between crustal provinces that were previously mapped using geophysical anomalies and lithologic correlations. Except for three surface samples of Ortonville granite near Ortonville (location a), the samples shown in Figure 1 are taken from cores obtained from the 1987-1988 drilling program of the Minnesota Geological Survey in west-central Minnesota (Southwick et al., 1990). All samples are felsic to intermediate plutonic rocks except those at locality e, which are similar in appearance to schists of the Little Falls Formation.

It can be seen from Figure 1 (from Southwick et al., 1990) that to the east of the Penokean Tectonic Front (PTF) the Nd model ages of samples are Early Proterozoic (~2.3 Ga), similar to results obtained by Spencer (1987) and Horan et al. (1986) for granitic rocks and mafic dikes in the St. Cloud area of central Minnesota. One exception is sample h, located very near the PTF boundary, which helps to relocate the boundary more precisely. Model

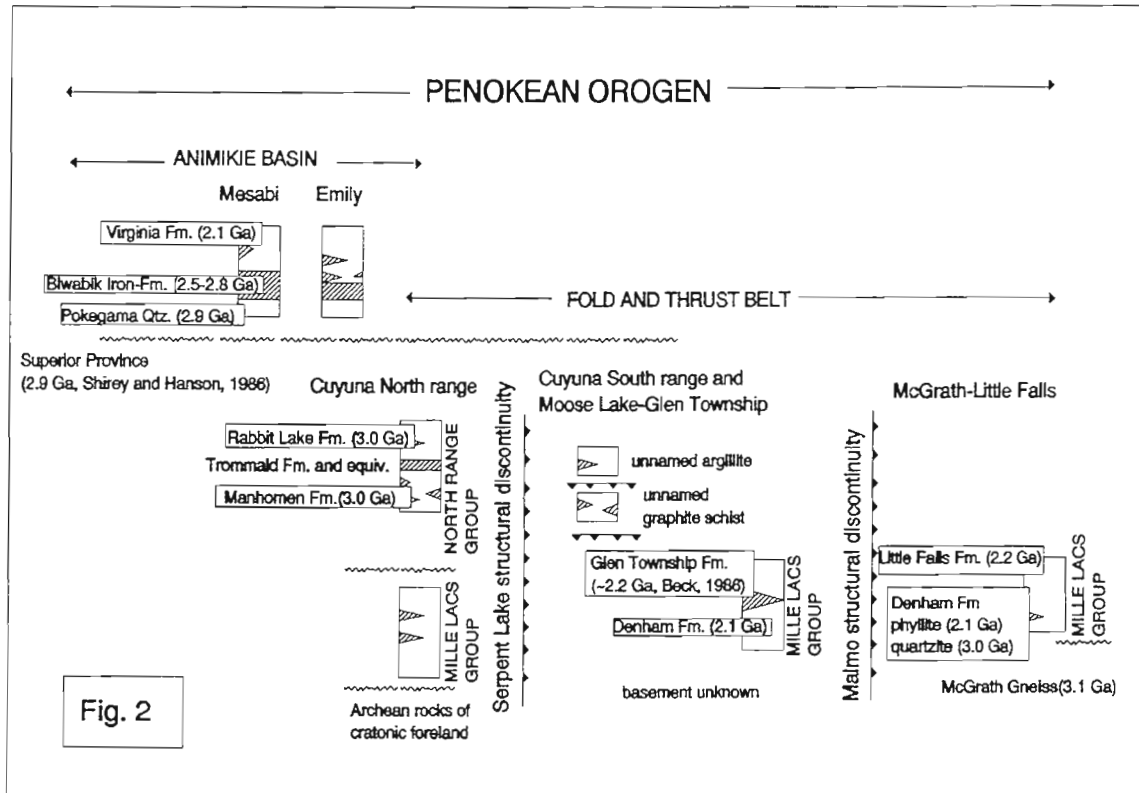


ages of three Ortonville granites are about 3 Ga. They have ϵ_{Nd} of about -5 at 2.6 Ga, their Rb-Sr isochron age, suggesting a crustal history (Goldich et al., 1970). Two samples of biotite gneiss from the McGrath gneiss northeast of the map area in Figure 1, also have model ages of about 3.2 Ga. The McGrath Gneiss is in the same block as the Ortonville Granite, i.e., located between the Great Lakes Tectonic Zone (GLTZ) and the Appleton Geophysical Lineament (AGL). Granites within Archean terranes and near the Penokean Tectonic Front have Late Archean model ages of about 2.8 Ga (b, c, d). These rocks could be: 1) Early Proterozoic granites with extensive contamination from this structural block or 2) juvenile Late Archean granites.

In addition to the granitic samples, we have analyzed several Early Proterozoic sedimentary rocks that predate the Animikie Group (Figure 2). The geological interpretation on Figure 2 is from Southwick et al. (1988), Southwick and Morey (1991), and Morey and Southwick (1993). Quartzofeldspathic units of the Mille Lacs Group along an abandoned stream channel near Denham, Minnesota have model ages of about 3 Ga and are indistinguishable in their Sm/Nd systematics from the Ortonville Granite and McGrath Gneiss. In contrast, schistose units of the Mille Lacs Group, including the Little Falls and Denham at several localities within the Denham, Royalton, and Belle Prairie quadrangles have a dominant Early Proterozoic provenance. The Manhomen and Rabbit Lake Formations from the Merritt and Hilcrest cores in the Cuyuna North range (Grout and Wolf, 1956) have model ages of about 3 Ga.

The Pokegama Quartzite has a Late Archean provenance (2.9 Ga) and the Biwabik has a mixed character (2.5-2.8 Ga, Hemming et al., 1992). The Virginia Formation has an Early Proterozoic provenance (~2.1 Ga, Hemming et al., 1992). Accordingly, in the Mesabi Range the Animikie Group records an evolution in the provenance from Archean sources at the base to dominantly Early Proterozoic, mantle-derived sources at the top. The Thomson Formation near Duluth, MN and the Tyler Formation near Hurley, WI have Early Proterozoic provenance (2.1 Ga). These results are consistent with the

foredeep model proposed by Southwick et al. (1988) for the Animikie Basin in which the Thomson Formation and related orogenic turbidites are derived from the Penokean highlands.



REFERENCES CITED

- Beck, Warren, 1986, Ph.D. thesis, Univ. of Minnesota.
 Goldich, S. S., Stern, C. E., and Stern, T. W., 1970, GSA Bul. v. 81, p. 3671.
 Grout, F. F., and Wolf, J. F., Sr., 1956, Minnesota Geol. Sur. Bulletin 36.
 Hemming, S. R., McLennan, S. M., and Hanson, G. N., 1992, ILSG, v. 38, p. 35.
 Horan, M. F., Spencer, K. J., and Hanson, G. N., 1986, Precambrian Research, v. 37, p. 323.
 Morey, G. B., and Southwick, D. L., 1993, Econ. Geology, v. 88, p. 104.
 Shirey, S. B., and Hanson, G. N., 1986, Geochim. et Cosmochim. Acta, v. 50, p. 2631.
 Southwick, D. L., Setterholm, D. R., and Boerboon, T. J., 1990, Minnesota Geol. Sur. Information Circular 31.
 Southwick, D. L., Morey, G. B., and McSwiggen, P. L., 1988, Minnesota Geol. Sur. Report of Investigations 37.
 Southwick, D. L., and Morey, G. B., 1991, USGS Bulletin 1904C.
 Spencer, K. J., 1987, Ph.D. thesis, SUNY Stony Brook.

EXPLORATION AND MINING ACTIVITIES OF INDUSTRIAL MINERALS IN NORTHWESTERN ONTARIO

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The "Northwestern Ontario Industrial Minerals Program" was initiated, in 1987, as part of a province-wide strategy to stimulate development of Ontario's industrial mineral resources and related manufacturing industries. The Industrial Minerals Program provides assistance to prospectors and industry by conducting property visits, sample preparation, analyses and discussion relating to the industrial mineral industry.

There are over 50 industrial mineral commodities known to occur within Northwestern Ontario. Current production includes: one granite dimension stone quarry producing blocks and slabs of pink granite for use as monument and dimension stone; a second dimension stone quarry started production in July 1992 and produces rough blocks and slabs of green and yellow granite; one quartz quarry which produced 17,000 tons of crushed quartz, one crushed red granite quarry which produces material for landscaping and precast concrete and one peat producer which began harvesting in November, bagging of the peat will commence in April with a forecast production of 200,000 bales of horticultural peat for 1993.

This poster displays current producers, sites of advanced exploration and high potential areas. Detailed information on all the properties is available from the Resident Geologists' Office, Ministry of Northern Development and Mines, 435 S. James St., Thunder Bay, Ontario, P7C 5G6.

Exploration and prospecting is currently under way to evaluate a number of properties for their dimension stone, quartz, fluorite, amethyst and graphite potential.

Northwestern Ontario includes the Resident Geologists' Districts of Kenora, Red Lake, Sioux Lookout, Thunder Bay, Beardmore-Geraldton, and Schreiber-Hemlo.

The program is jointly funded by the CANADA-ONTARIO 1991 Northern Ontario Development Agreement (NODA), a subsidiary agreement to the Economic and Regional Development Agreement (ERDA) signed by the Governments of Canada and Ontario.

PREHISTORIC COPPER MINING IN THE LAKE SUPERIOR BASIN

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Thousands of prehistoric mines are located in the native copper-bearing volcanic rocks of the Lake Superior region. The majority of these ancient copper mines are in Michigan, on the Keweenaw Peninsula and on Isle Royale; others are in Wisconsin and Ontario. The prehistoric miners were formidable prospectors: virtually all of the historic mines of the world-class Keweenaw native copper district were developed on prehistoric mining sites.

The prehistoric mines are shallow pits, generally 10 to 30 feet across and 5 to 20 feet deep. However, prehistoric excavations as much as 60 feet deep have been reported. The pits are usually found along the strike of the copper-bearing stratigraphic horizons. In some areas the prehistoric mining pits are so extensive their depressions form linear trends several miles in length. Pits that crosscut the interbedded conglomerates and basalt flows have been found along the strike of fissure deposits. Excavations on raised beaches and in glacial drift suggest the prehistoric miners also recovered float copper.

Little is known about the culture of the prehistoric miners. No burial sites, dwellings, pottery, or petroglyphs have been found. Who were these prehistoric miners? When and how did they mine these copper deposits? The following discussion offers some possible answers to these questions.

Paleo-Indian cultures moved into the Great Lakes basin about 11,000 years ago as the glacial ice retreated. These nomadic hunters occupied the shores of the glacial lakes and are assumed to be the predecessors of the prehistoric mining culture, often referred to as the Old Copper Culture. The Old Copper Culture supposedly reached its height during the Late Archaic Stage between 3000 and 4000 years ago. Charcoal recovered from mining pits on Isle Royale has been dated at 3500 to 4000 years old. The Late Archaic cultures are the predecessors of the Woodland Stage Indians who occupied the Great Lakes region in historic times.

When the prehistoric mining period began is unknown. 11,000 years ago the lake level was at an elevation of about 1100 feet (Lake Duluth Stage). This high water level would have drowned much of the copper-bearing formations in the basin. However, some of the more extensive prehistoric workings, such as those on the Cliff Range, are above 1100 feet and would have been accessible by watercraft. Many copper artifacts have been found buried under Nipissing lake sediments, indicating copper was mined prior to that high-water period (about 5000 years ago). Charcoal recovered from a prehistoric site on the Keweenaw Peninsula is reported to have been dated at about 7000 years old. When and why the prehistoric mining ceased is also unknown. There are no historic accounts of Woodland Indians mining or having knowledge of mining. However, the Woodland culture did possess copper implements.

Excavations of the abandoned pits have revealed clues about the mining methods used by the prehistoric mines. All of the pits contain numerous hammer stones, and the wooden remains of shovels, large bowls, levers, cribbing, and ladders have been discovered in several of the deeper prehistoric workings. Copper tools including knives, chisels, and gads have been found in many of the pits. Charred wood or charcoal is found in nearly all of the prehistoric workings. At the bottom of some excavated pits, irregular sheets of native copper were found protruding from the floor of the pit. The work was abandoned before the copper was dislodged from the surrounding rock.

The most common mining tool used by the prehistoric miners was the hammer stone. Tens of thousands of hammer stones have been observed scattered on the surface around the workings, in piles of waste rock, and buried in the mine pits. The hammers are oblong, water-worn boulders composed of hard crystalline rock. The hammer stones range in size from 4 to 10 inches across and generally weigh

between 5 and 15 pounds. Some of the hammers have a groove chiseled or ground around the stone for attaching a handle, however, the vast majority are ungrooved. Many of the stone hammers are broken. The oblong ends are cracked, chipped and fractured from repeated blows.

There were probably two distinct stages of mining. Initially, copper was recovered from the weathered surface outcrops. The surface rock enclosing the copper, weakened and fractured by physical weathering processes, was easily removed using stone hammers. When solid rock was encountered, the outcrop was abandoned for easier digging elsewhere. The surficial copper exposures were probably reworked over many centuries as frost action and ice wedging further fractured the solid host rock, loosening the native copper.

The second stage began when the easily mined surface outcrops were depleted. A technique was developed to recover the copper from the solid, unweathered rock. Based on the evidence discovered in the excavated pits, and the incredibly large number of hammer stones found in or surrounding the pits, the following scenario is proposed as the technique used by the prehistoric miners.

The prehistoric miners used a combination of thermal and mechanical stress to break the solid, brittle rock enclosing the malleable copper. A fire was built in the pit, heating the copper and the surrounding rock. Due to the high thermal conductivity of copper relative to basalt, the copper heated more rapidly. Thermal stress was generated by the high thermal gradient between the hot copper and the relatively cool basalt. As copper has about three times the thermal expansion of basalt, the cohesion between the copper and the surrounding rock was broken and mechanical stress was generated due to the increased volume.

After sufficient heat was applied, the miners hurled dozens of hammer stones at the heated rock surrounding the copper. The combination of thermal stress, mechanical stress, and the shock delivered by the pelting of hammer stones cracked and shattered the basalt. When the pit cooled to permit entry, the miners cleaned out the ashes, coals and waste rock using wooden shovels. Hammer stones and copper chisels and gads were used to remove the remaining fractured rock to free the native copper.

The above process was applied repeatedly, deepening the pit until the copper pinched out. Ladders made from tree trunks were used in the deeper pits. Dewatering was a problem in some of the prehistoric mines. Wooden bowls were used to bail water from the pits. In some pits drains were cut in the rock to dewater the workings. At other sites, where drains ran across drift or waste rock, the miners lined the drains with birch bark or used cedar troughs to prevent water from seeping back into the workings.

Copper obtained by the prehistoric miners was fabricated into various implements including knives, daggers, axes, arrowheads, spearheads, chisels, gads, hooks, gaffs, fleshers, scrapers, awls, needles, bracelets, earrings, beads, and bells. The malleable metal was worked cold by beating it into shape. There are no indications that Old Copper Culture Indians melted and cast copper objects. The copper was traded extensively; native copper artifacts have been found from Canada to Central America. The majority of copper artifacts are found among the works of the mound building cultures located throughout the Mississippi River Valley from the Great Lakes to Louisiana.

The prehistoric copper mines of the Lake Superior region are perhaps the oldest, and certainly the most extensive, of mankind's prehistoric mining endeavors. Why haven't these prehistoric mines been the focus of comprehensive archeological studies? Why were the copper mines abandoned; and what became of the industrious and persevering miners who produced the copper that became widespread and an integral part of other Indian cultures? Without further archeological studies and discoveries we may never know.

SIGNIFICANCE OF STRAIN PATTERNS IN ARCHEAN GREENSTONE BELTS

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Averaged strain data (over 250 measurements) from 15 Archean greenstone belts or parts of greenstone belts in the Superior Province of Canada and southern Africa are shown in Fig. 1. It is hard to see any clear pattern to the data as a whole, and there are no common elements shared by all the greenstone belts represented. The strains are generally modest, with strain magnitude, ϵ_s , less than 2, and $X/Y < 5$ and $Y/Z < 10$ in over 95% of individual determinations. Strain symmetry varies from pure flattening ($v=1, k=0$) to nearly pure constrictional ($v=-1, k=\infty$), but flattening strains are decidedly more common than constrictional strains. The range of strain values found within individual greenstone belts is as great as the range of average strains shown in Fig. 1. The strain is usually associated with the 'main' deformational event in each greenstone belt. In many instances there is evidence for an early tectonic event producing recumbent folds and nappe-like structures without any apparent strain of the rock or imposition of a metamorphic fabric.

Strain magnitudes within individual greenstone belts may be greatest along the margins of the belts, or in zones of shear internal to the belts. Strain profiles across belts are typically rather flat. There may or may not be variations in strain related to position in major folds. In two greenstone belts, including the Vermilion district in northeastern Minnesota, there are clear patterns of variation in strain symmetry, with alternating zones of constrictional and flattening strains, roughly parallel-sided and parallel to the adjacent greenstone belt boundary.

It is not easy to summarize the findings regarding the orientations of principal strains, because these must be considered in relation to the trends of individual greenstone belts. There are certain features that seem clear, however. The maximum principal stretch direction, X, is typically sub-vertical or steeply inclined and the minimum principal stretch direction, Z, is sub-horizontal in nearly all greenstone belts. Thus the XY-plane is steep to vertical. It is typically found that the X-direction and XY-plane are parallel to the mineral lineation and schistosity or cleavage, respectively, of a low-grade metamorphic fabric in the rock, and also to the principal directions of magnetic susceptibility. The cleavage and XY-plane of strain generally strike sub-parallel to the boundaries of the greenstone belt with granitoids or adjacent belts of high-grade rocks. They are also parallel to the axial planes of folds produced during the 'main' deformation that also produced the metamorphic fabric. In many belts, especially where parallel-sided, both cleavage and XY-plane of strain also strike parallel to bedding. The near parallelism of cleavage (and XY-plane of strain) with bedding in rocks that show only modest deformation is a common feature of greenstone belts and one that distinguishes greenstone belts from slate belts found commonly in younger orogens. In large areas of some greenstone belts, in fact, the deformation is so modest that cleavage is absent.

The magnitudes of strain measured in greenstone belts are comparable to those measured in younger rocks in various tectonic environments involving low-grade metamorphism. For example, the field of measured strains in greenstone belts (Fig. 1) is to a large degree co-extensive with the field of states of strain in several hundred slates. In both cases strains are predominantly in the flattening field. Greenstone belts do not display the very large regional strains measured or inferred in the high grade and thus more mobile cores of either Archean or younger orogenic belts.

The strain patterns in greenstone belts have been interpreted in terms of several principal kinematic models: 1) diapirism - piece-meal inversion of unstable density stratification or subsidence between centers of balloon inflation; 2) crustal shortening in pure shear or coaxial flattening; 3) crustal-scale shear zones; or 4) transpression. Given sufficient data in three dimensional space, it would be possible to discriminate among these various models based on the strain pattern, although several alternative models can probably be found to account for most natural data sets.

The common occurrence in greenstone belts of plane strain to flattening strain with XY planes striking parallel to the margins with granitoids and with a steep X direction is generally consistent with both diapiric and transpressive origins for the strain-producing deformation. In terms of structural setting, however, many of the measured strains of both flattening and constrictional types in Archean greenstone belts are associated with zones of ductile shear, of either thrust or strike-slip nature. The large variation in strain magnitude and symmetry in individual greenstone belts is consistent with the pattern of variations of strain found in ductile shear zones, although not, in most cases, with the development of simple shear alone. The strain patterns require a more complex scenario, such as transpression, simple shear superposed on a preexisting strain or progressive volume loss accompanying the shear. Such scenarios can account for either flattening or constrictional strains. The strain patterns and field relationships also argue more generally in favor of domainal behavior of the deformation in greenstone belts. Such behavior has been described most clearly in the deformation of younger massive crystalline bodies, in which lozenges of weakly deformed rock are bordered by anastomosing zones of shear. This is a kind of deformation partitioning,

and strain can vary greatly with position in the body, and at any location bear little relationship to the bulk strain. The extent to which this may occur in greenstone belts has yet to be determined.

The phenomenon of weak or non-existent strain in steeply dipping rocks so common regionally in greenstone belts is found in a number of duplex structures in younger fold and thrust belts, and it may well be that the steep dips in greenstone belts are attained during a stacking and imbrication process similar to that which occurs in fold and thrust belts or accretionary prisms. Modern work in greenstone belts increasingly suggests this kind of tectonic history.

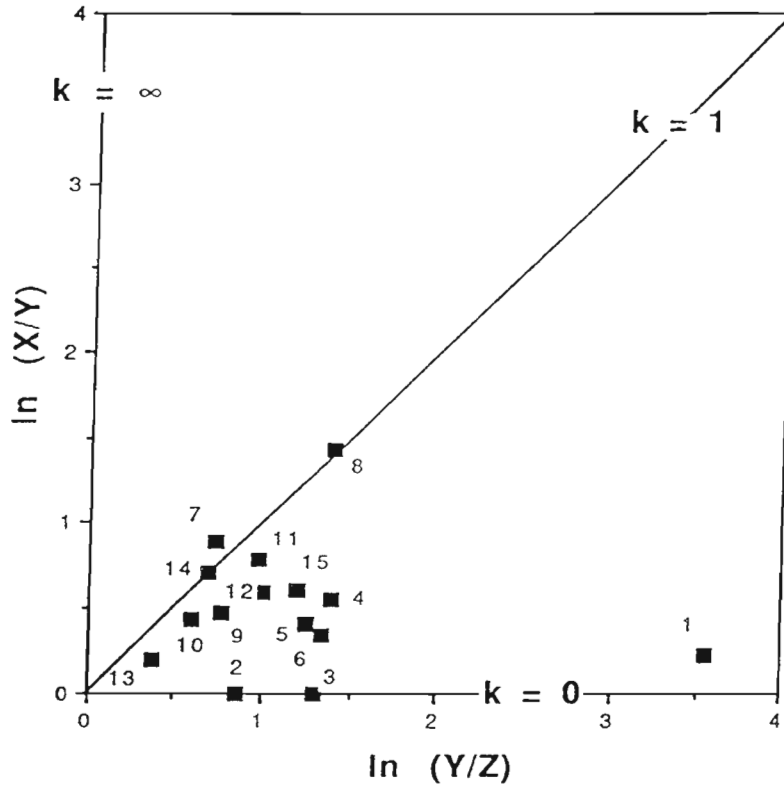


Fig. 1. Average strains from 15 Archean greenstone belts or parts of greenstone belts plotted on a logarithmic Flinn diagram. Each point represents from 1 to 70 individual strain determinations. 1 - Lake St. Joseph, Ontario; 2 - Lac des Mille Lacs, Ontario; 3 - Shebandowan Lakes, Ontario; 4 - Shagawa Lake, Vermilion district, Minnesota; 5 - Assegaai, South Africa; 6 - Rainy Lake-Seine River fault zone, Minn./ Ont.; 7 - Vermilion district, Minnesota; 8 - Umvuma, Zimbabwe; 9 - Barberton, South Africa; 10 - Bulawayo, Zimbabwe; 11 - Tati, Zimbabwe; 12 - Fort Victoria, Zimbabwe; 13 - Shabani, Zimbabwe; 14 - Lower Gwanda, Zimbabwe; 15 - Pietersburg, South Africa.

GRAVITY ANOMALIES OVER WISCONSIN MASSIVE SULPHIDE DEPOSITS

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Geophysical exploration for massive sulphide deposits normally proceeds from an initial airborne EM survey to ground follow up utilizing ground EM methods and magnetics. Gravity is seldom used, except in a postmortem situation if one is fortunate enough to encounter sulphides during drilling. This talk will discuss results from six gravity surveys which were conducted over known massive sulphide deposits in Wisconsin. Results are summarized below:

CRANDON - The largest of the Wisconsin deposits has a 2.0 milligal anomaly.

FLAMBEAU - A maximum anomaly of 1.2 milligals is located over this deposit.

LYNNE - A gravity anomaly of 0.9 milligals is slightly displaced from the EM anomaly due to the shallow dip of the deposit.

PELICAN RIVER - An anomaly of 0.5 milligals occurs over this deposit.

BEND - Results are complicated by an extremely steep gravity gradient and the location of the survey line over a deep portion of the deposit. Even with these problems, an anomaly of 0.3 milligals is easily defined. Had the survey line been located over the center of the deposit, a larger gravity response would have been measured.

CATWILLOW - An anomaly of approximately 0.25 milligals was measured over this deposit.

Model calculations based on a Flambeau type deposit buried at various depths will be shown. A clear gravity response can still be seen from a burial depth of 300 feet.

STRUCTURAL AND STRATIGRAPHIC FRAMEWORK OF THE WESTERN WAWA AND QUETICO SUBPROVINCES-COOK TO SIDE LAKE AREA, MINNESOTA

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This presentation is an overview of the geology of Archean rocks in the Cook to Side Lake area (**Field Trip 3**, this conference) and highlights aspects of the geology of this district that relate to the evolution of the southern Superior Province. The Wawa and adjacent Quetico subprovinces in Minnesota share many of the attributes of volcano-plutonic and metasedimentary belts elsewhere in the Superior Province. Recent mapping studies and comparison with analogs indicate that this terrane evolved during accretion of island arcs and other constructional elements to a protocontinent by a process of northward directed subduction. Evidence for the earliest tectonic events is scattered throughout the subprovinces. In Minnesota the Wawa subprovince differs from many other greenstone-granite terranes in that its southern part is dominated by supracrustal rocks, in contrast to many other belts dominated by large plutonic masses that are separated by thin septa and triple-point-like nodes of greenstone. Thus, the geometric distribution of map units and correlation with mapping in well-exposed parts of the belt indicate that significant products of the earliest deformation have been preserved and that that deformation has affected a large geographic region.

The two main regional deformation events in the Wawa subprovince are D₁, which produced locally recumbent, south-verging folds and strata-parallel thrust faults, and a later event, which resulted in pronounced upright folds, dextral transpression manifest in both folds and faults, and the regional prograde metamorphism to greenschist and amphibolite facies associated with D₂ deformation. The D₁ event did not produce a metamorphic cleavage in rocks of this area. In fact, studies of strain indicate that much of the early deformation occurred before lithification of the sedimentary rocks, and a direct link can be drawn between the style of early deformation and the construction of depocenters. In contrast, D₂ produced east-trending cleavage, and meter- to kilometer-scale folds which can be seen in outcrops of hinge zones and inferred from the angular relationships between cleavage and bedding. The cessation of these deformation events can be broadly correlated across the subprovince and adjacent areas by geochronologic studies (see field guidebook for references). Recumbent folding in D₁ was complete by ~2685 Ma when the Britt granodiorite was emplaced, and the main metamorphic event of D₂ is constrained by the ~2674 Ma-Shannon Lake granite that intruded rocks deformed during both D₁ and D₂.

The progression from D₁ to D₂ represents a significant shift in the style of tectonism that occurred over a broad area of the southern Superior Province. Recumbent D₁ folds have been described from the southern part of many greenstone belts in the Wawa, Abitibi, and Pontiac subprovinces. Southward vergence, which is indicated in nearly all of these districts, implies that early north-south compression during D₁ produced *subprovince-wide*, north-over-south, low-angle thrusting. Although the northwest trend of D₂ compression is similar to that of D₁, the character of the vergence changed from that dominated by subduction and south-verging imbrication (D₁), to the intense deformation of D₂, which included oblique horizontal shortening under conditions of moderate metamorphic grade.

The change from D₂ to D₃ is more enigmatic. D₃ is assigned to all structures in the Cook area that post-date metamorphism and emplacement of late plutonic rocks. Structures generated in D₃ include local crenulation folds, a weak fabric in some late plutons, and faults that bound rocks of contrasting metamorphic grade. A large dome of high metamorphic grade and the associated reorientation of D₂ fabrics in the Cook area is inferred to be the product of localized D₃ uplift that was synchronous with emplacement of late alkalic plutons. Fault-bounded panels of contrasting metamorphic grade define the major subdivisions of the Wawa and Quetico belts; however, most of those subdivisions were initiated during earlier deformations.

Magnetic studies of the Keweenawan Age Chengwatana Lava Flows
Near Dresser Wisconsin.

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Thirty-three oriented core samples were collected at seven sites in five lava flows near Dresser, Wisconsin. The locations and names of the flows are those of Cordua (1989). Sites 1 and 2 are Dresser Flows located in the northeastern part of the Dresser Trap Rock Quarry. Sites 3 and 4 are from the Eagle Peak Flows, exposed on ridges to the northwest and southwest of the town of Dresser. Site 5 is in the Ski Trail Flow; Sites 6 and 7 are in the Pipeline Flow which directly overlies the Eagle Peak Flow at site 4.

An hysteresis loop conducted on a sample from the Eagle Peak Flow indicated a H_{cr}/H_c ratio of 7.54 and J_{rs}/J_s ratio of 0.074. Thermal demagnetization experiments reveal a Curie temperature of about 582°. The hysteresis properties and the Curie temperature all indicate a multi-domain magnetite as the primary magnetic carrier. The samples were stepwise A.F. demagnetized to 80-100 mT. Some samples were also thermally demagnetized to 582° C. The magnetic results were analyzed using a principle component analysis procedure of Kirschvink (1980), to obtain a characteristic remanent magnetic direction. A number of samples reveal a highly viscous component with a direction more or less random. Such magnetization could have been acquired by lightning strikes. Sites 1-3 show normal directions of magnetization which are generally northwesterly and consistent with the 1.05Ga apparent pole for the North American craton. Some samples from the Eagle Peak Flow (sites 3 and 4) show reversed overprint which is most likely due to the reversed magnetism of the Ski Trail Flow (site 5). The Ski Trail Flow is magnetized approximately antipodal to that of sites 1 through 3. Sites 6 and 7 show variable normal directions with high α 95 values. These results refine the work of Feeney (1990).

Two east-west magnetic traverses perpendicular to the strike of the flows seem to show correlation with the magnetic parameters of the surface rocks. However, modelling requires fairly deep sources on the order of 500-3000 ft. deep to account for magnetic anomalies of 2000 nT. Individual surface flows are estimated to be only 100 ft. thick, and therefore too thin to produce the magnetic signature alone.

Summary Results

Lava Flows oldest-youngest	site #	N	D	I	Plat,	PLong,	$\alpha 95$
Dresser	1	3	290	42	185	30	17
Dresser	2	4	295	47	186	36	20
Eagle Peak	3	3	277	31			
Eagle Peak	4	4	292	55	192	39	10.1
Ski-Trail Flow	5	5	103	-62	205	37	29.1
Pipe Line Flow	6	5	269	63	213	29	25
Pipe Line Flow	7	4	212	60	244	2	50

References

- Cordua, William S., 1989, A Summary of the Bedrock Geology of the Dresser-St. Croix Falls area, Polk County, Wisconsin and Chisago County, Minnesota. 53rd Annual Tri-State Field Conference Guide Book, River Falls, WI.
- Feeney, John, 1990, Paleomagnetism of Keweenawan Age Basalts of the Chengwatana Volcanic Group in Polk County, Wisconsin. Unpublished MS thesis, University of Wisconsin-Milwaukee, 218 pp.
- Kirschvink, J.L., 1980, The Least-squares line and plane and the analysis of paleomagnetic data. Geophys. J.R. Astr. Soc. 62, 699-718.

THE NORTH COLDSTREAM MINE, BURCHELL LAKE, NORTHWESTERN ONTARIO
LAVIGNE, Maurice L. and SCOTT, John F., Ministry of Northern
Development and Mines, Suite B002, 435 James St. S.,
Thunder Bay, ON P7E 6E3

Copper mineralization was discovered near the northeast shore of Burchell Lake in 1872. Copper was produced from the site of the North Coldstream Mine in 1903, 1906, 1916-17, 1957-58 and 1960-67 for a total of 102,000,000 pounds. Most of this production occurred from 1960 to 1967. The ore contained 2% copper, 0.012 ounce per ton gold and 0.22 ounce per ton silver. In addition, one of the many ore lenses contained 0.2 to 0.4% cobalt and 0.5% nickel. All ore lenses are anomalous in Bi and Sb.

The mineralization consists of lenses with a high density network of chalcopyrite and pyrite veinlets. Some massive and disseminated mineralization also exists. The lenses are sometimes interconnected by lower-grade material, and have a maximum horizontal dimension of 70 m x 70 m and plunge at 50° to the east.

They are hosted by a 300 m x 120 m massive silicalite. Where it is unmineralized and unsheared, it is massive, aphanitic, buff and mauve in colour and textureless. It consists of 92% to 95% SiO₂, 1.90% to 3.89% TiO₂, 1.42% to 2.25% Al₂O₃ and 0.17% to 2.01% Fe₂O₃ (total Fe). One portion of this siliceous complex contains 5.67% to 8.48% TiO₂ and 40% to 85% SiO₂. The more siliceous rock, with abundant titano-magnetite needles, surrounds a lens of aphanitic, talcose, ultramafic rock which also has abundant titano-magnetite.

The siliceous complex is hosted by a gabbroic anorthosite. Gabbro immediately south of the complex contains 1.62% TiO₂ and anorthosite east of the complex contains 0.51% TiO₂.

Intense ductile deformation which postdates the formation of the siliceous rocks has obscured their contact relationship with enclosing gabbro and anorthosite.

The parameters of this deposit make it unique. The metal association and host imply a magmatic origin, however, an exhalative model can also be accommodated, albeit with equal difficulty.

SUMMARY OF CURRENT WORK IN CENTRAL MINNESOTA AND FUTURE PLANS

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The Mineral Potential Section of the Minerals Division is working on a project to compile and index minerals information of a large part of Central Minnesota, Region 3, (see index map). The purpose is to serve land use planning within the D.N.R. and by counties, to encourage private exploration through better data access, and to serve agency planning of future programs. During the next three months, we will finish an inventory of the historical information, complete a comprehensive digital database, ore mineral occurrences, and applicable ore deposit models. This work will include: Geologic maps, airborne magnetic surveys and gravity surveys done by the Minnesota Geological Survey; Geochemical surveys done by the United States Department of Energy and the Minnesota Department of Natural Resources and; Exploration mapping and drilling done by private industry. This poster summarizes progress of the geophysical part of this effort and presents combined results of geophysics with ground water and lake sediment geochemistry.

A contract has been completed by Dr. Allan Spector to make an inferred geologic map of the twenty township Shephard Area at a scale of 1:62,500 and a second twelve township map extending this area to the northeast. To make these maps Dr. Spector used the M.G.S. airborne magnetic survey, ground gravity surveys and all available geologic data, which included M.G.S. maps and published drill data, and D.N.R. General Exploration File data. This information was used to construct profiles which were then used to interpret geology. An important aspect of this contract was construction of 1:62,500 scale maps displaying area mineral potential as modeled from known mines located in similar Precambrian terrains.

Barry Frey logged available core and cuttings, then density and magnetic susceptibility measurements were made. Nineteen outcrops and twelve rock dumps were also sampled and geophysical measurements made on selected samples. These density and magnetic susceptibility measurements provide accurate data for computer modeling of geologic features based on magnetic and gravity surveys. Eighty miles of detailed magnetic traverse was completed along roads using an A.T.V. for transportation. Ground magnetic susceptibility profiles provide data perpendicular to the flight lines of airborne surveys and also provide more accurate spacial relationships for interpretation than airborne surveys.

Another contract was completed by Dr. Don L. Shettel Jr. and Dr. Patrick O'Hara to interpret three existing geochemical datasets that cover a portion of Central Minnesota using state of the art statistical and geochemical modeling methods. Drs. Shettel and O'Hara constructed anomaly maps similar to the one shown here for gold and base metals.

When finished the Central Minnesota (DNR Region 3) mineral potential evaluation will be a composite of these programs readily available to the public in digital format. The objective is to enhance the availability of data for use by all our clients in the public and private sectors.

A METAMORPHOSED DIKE IN THE PRECAMBRIAN WATERLOO QUARTZITE, OLD PORTLAND QUARRY, DODGE COUNTY, WISCONSIN

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The 1.63 - 1.76 b.y. Waterloo Quartzite is exposed east of Waterloo near Portland, WI in several small abandoned quarries. The author discovered a metamorphosed dike several years ago in the northwest wall of the southernmost quarry during continuing study of this quartzite.

The dike (attitude 152° near vertical) is about 0.4 meters wide and is exposed for about 10 meters. It cross-cuts near horizontally bedded quartzite. Mesoscopically, the dike shows unusual adjoining plastic and brittle deformation. The brittle deformation is similar to the blocky fracturing produced by weathering of some aphanitic igneous rocks. Opaques are preferentially concentrated in the fractures.

The dike was previously identified as an ultramafic intrusive consisting of 10-30% opaque minerals, talc and minor quartz based on petrographic examination (Luther, 1992). The following bulk chemical analysis indicated a need for re-examination.

SiO ₂	51.0	Al ₂ O ₃	15.4	CaO	0.16
MgO	0.81	Na ₂ O	<0.01	K ₂ O	3.31
FeO _t	19.9	MnO	0.06	TiO ₂	4.80
P ₂ O ₅	0.14	LOI	4.30	Total	100.2

EDA of the opaque phase, XRD of the phyllosilicate, and reflected/transmitted light petrography shows the rock to consist of:

titanohematite	10-30%
muscovite	50-70%
quartz	10-30%
epidote	<1%

Microscopically, there is a weak foliation (due to muscovite) which trends around 0.5 mm clots composed of quartz, muscovite and opaque grains. These clots may be relicts of porphyroblasts or phenocrysts.

This dike was emplaced as basalt or perhaps a lamprophyre in the sandstone precursor of the Waterloo Quartzite. It was subjected to weathering and/or groundwater alteration which removed Ca, Na and Mg while concentrating Ti and Fe as Fe⁺³. The K was retained as a K-bearing clay such as illite. After alteration of the dike, the rocks were regionally folded with development of foliation and then subjected to andalusite-grade (probably highT/lowP amphibolite facies) metamorphism with attendant generation of the current dike mineral assemblage.

REFERENCE

Luther, F.R., 1992, The Waterloo quartzite at the old Portland quarry, The 56th Annual Tri-State Geology Field Conference Guidebook to the Geological Setting of Whitewater, Wisconsin and Surrounding Areas, Jack Travis, ed., p. 51-61.

EARLY PROTEROZOIC MAGMATISM AND TECTONISM RELATED TO SOUTHWARD-DIPPING SUBDUCTION AND MICROCONTINENTAL ACCRETION IN CENTRAL WISCONSIN

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Three major Precambrian terranes are present in central and northern Wisconsin. From south to north they are: (1) the central Wisconsin terrane (CWT), which consists primarily of 2,750-3,000 Ma gneisses, 2,500 Ma gneisses, and 1,820-1,890 Ma igneous rocks emplaced into these gneisses in a continental-arc setting during the Penokean orogeny; (2) an island-arc belt formed in northern Wisconsin during the Penokean orogeny at 1,810-1,890 Ma, which lacks Archean rocks; and (3) the southern margin of the Archean Superior Province and its overlying lower Proterozoic Marquette Range Supergroup rocks.

Archean and Penokean metamorphisms of the CWT each ranged from lower greenschist to upper amphibolite facies. Grade was typically lower to upper amphibolite facies at 2,800 Ma and lower amphibolite facies during the Penokean orogeny. A third metamorphic event, possibly at 2,500 Ma, at lower amphibolite facies, has been recognized in the Yellow River area in the vicinity of Pittsville. The grade of Penokean metamorphism is typically highest where Penokean intrusive rocks are most abundant. A notable exception is in the Yellow River area where Penokean plutons are very abundant but there was only low-grade alteration during the Penokean orogeny.

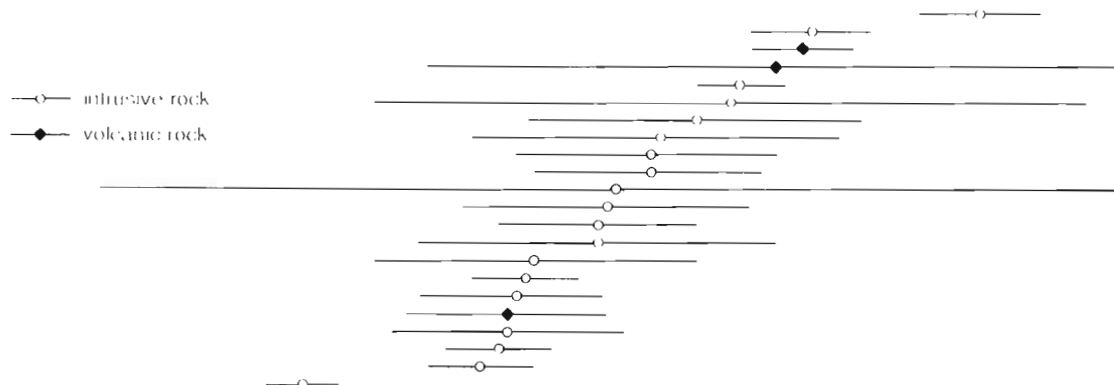
Most of the CWT underwent isoclinal, tight, and open phases of folding during the Penokean orogeny, but the Yellow River area escaped Penokean deformation. Because of the absence of Penokean deformation in the Yellow River area, 2,800 Ma isoclinal, tight, and open sets of folds are recognizable here, but folds of this age are generally difficult to identify elsewhere in the CWT because of overprinting by Penokean tectonism.

Many Penokean plutons and surrounding older rocks possess a well developed subvertical mineral lineation. Mineral lineation in the absence of foliation in numerous plutons suggests that the lineation is a product of diapirism. Along the Wisconsin River near Stevens Point, three sets of fold axes in Archean gneiss are parallel to each other, to mineral lineation in the gneiss, and to mineral lineation in Penokean intrusive rocks. Strain associated with diapirism during the late stages of Penokean igneous activity in this area is proposed to have rotated originally divergent fold axes into parallelism with each other and with mineral lineation. The locus of this diapiric uplift spatially corresponds with the greatest abundance of intrusive rocks and the highest grade of metamorphism in the Wisconsin River area.

Near the end of the Penokean orogeny the CWT was sutured to the island-arc terrane along a poorly defined northwest-trending boundary in central Wisconsin, and the island-arc terrane was sutured to the Superior Province along the Niagara fault in northern Wisconsin. The overlapping ages of igneous activity in the CWT and the island-arc terrane (Figure 1) imply simultaneous operation of two southward-dipping subduction zones during the Penokean orogeny (Figure 2) and approximately coeval closure of the two suture zones.

Petrographic and isotopic data from outcrops and subsurface samples suggest that the CWT does not extend into southern Wisconsin. The tectonic history of the CWT differs in several respects from that of the terrane north of the Niagara fault and from that of the Minnesota River Valley. The CWT is therefore interpreted to be an exotic microcontinent. Because of differences in tectonic history from one part of the CWT to another, it is possible that the CWT itself is composed of several smaller accreted terranes.

Zircon Ages, Penokean Arc Terrane



Zircon Ages, Central Wisconsin Terrane

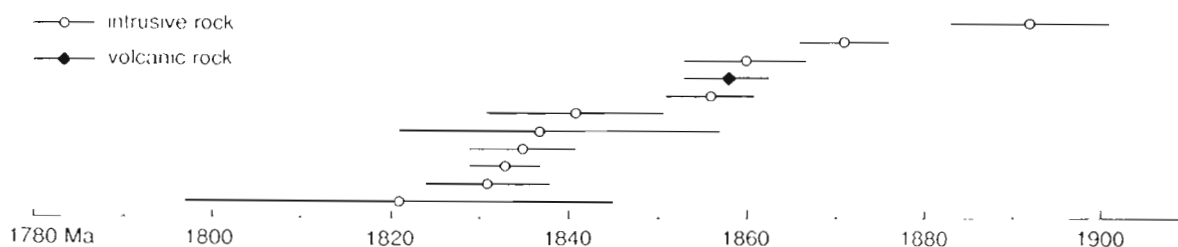


Figure 1. Zircon ages of Penokean intrusive and volcanic rocks in the island-arc terrane of northern Wisconsin and the central Wisconsin terrane. Horizontal lines represent error limits of ages. Data mainly from W.R. Van Schmus and Z.E. Peterman.

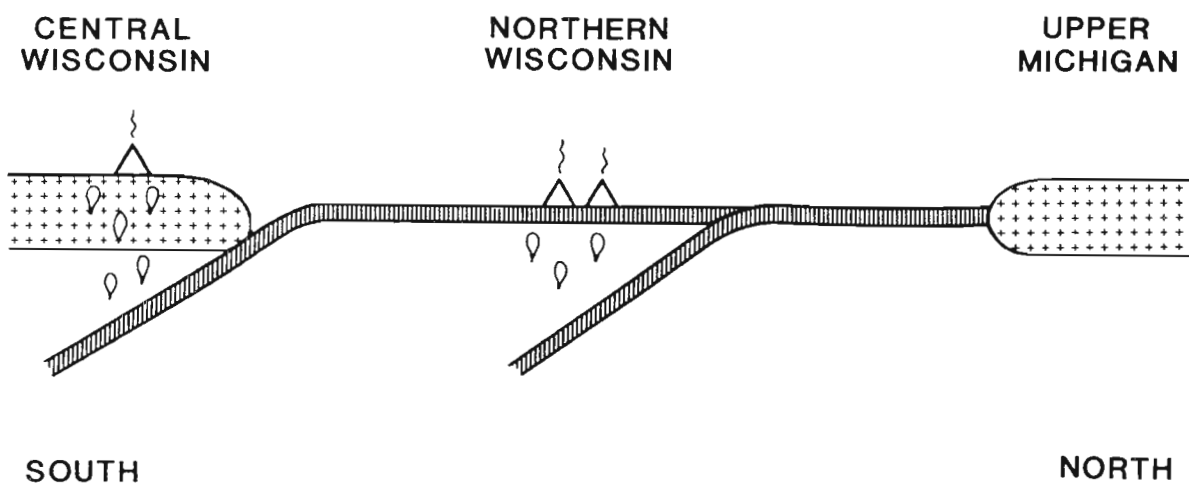


Figure 2. Tectonic model for the Penokean orogeny in Wisconsin.

EVIDENCE FOR LATE PALEOZOIC DISPLACEMENT ON THE KEWEENAWAN THRUST FAULT FROM FOLDED PALEOZOIC OUTLIERS IN MICHIGAN'S UPPER PENINSULA

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Geology Department, Macalester College, St. Paul, MN 55105

Two outliers of Paleozoic limestones are exposed in Michigan's Upper Peninsula over 150 miles from the nearest Paleozoic sediments of similar age in the Michigan basin. These two outliers, known as Limestone Mountain and Sherman Hill (Fig. 1) are composed of folded middle Ordovician-Devonian limestones and dolomites whose biostratigraphy and ages have now been detailed using conodonts. North-plunging synclinal structures are exposed in each locale. The underlying Precambrian-aged Jacobsville Sandstone is also folded harmonically with the Paleozoic limestones suggesting that the folding was post-Devonian and is likely related to reactivation of the Keweenawan thrust, which is exposed 7 miles to the west.

At Limestone Mountain conodonts (*Amorphognathus ordovicicus*, *Plectodina furcata*, *Belodina compressa* and *Periodon grandis*) representing Middle to Late Ordovician faunas #10 and #11 are present in the lower, upright 30 meter portion of the section. Faunas #7 and #8 (*Plectodina aculeata*, and a variety of fibrous conodonts) in a 25 meter thick section, overly the lower section and are exposed to the north on the west side of Limestone Mountain. Farther north is a thin section (~5 meters) of Silurian and Devonian carbonate. The presence of older-over-younger sediments requires a faulting solution, probably involving thrust faults that dip to the west (Fig. 1). Calcite and dolomite are mechanically twinned and the twin analysis resulted in a layer-parallel shortening strain (3.4%) that is oriented perpendicular to the trace on the Keweenawan thrust and parallel to the regional Appalachian orogen shortening fabric seen in carbonates of pre-Permian age in the Michigan basin (Craddock and others, 1993, Tectonics). Preliminary examination of conodonts from Sherman Hill carbonates has revealed the presence of *Periodon grandis*, *Belodina compressa*, *Plectodina furcata*, and abundant specimens of *Panderodus* sp. These species and the lack of *Amorphognathus ordovicicus* indicate a probable assignment to fauna #9, and a Middle Ordovician age. This quarry also exposes a north-plunging synclinal structure. Folded and cataclasized Jacobsville Sandstone is present at the base of the carbonate section.

In addition to the conodonts, we have discovered the presence of glass microtektites (Fig. 2) within the upper Ordovician carbonates in one sample from Limestone Mountain. The microtektites are uniform in diameter (50 microns), translucent, and have unabraded exteriors; they are clearly distinguished from reworked Jacobsville and St. Peter silica sand grains found in the dissolved residue. Microprobe chemical analysis of the microtektites indicates a deficiency of Al (1.3%) and enrichment of Na (15.3%) relative to Si (73%). The location of the Ordovician impact site associated with these microtektites is unknown.

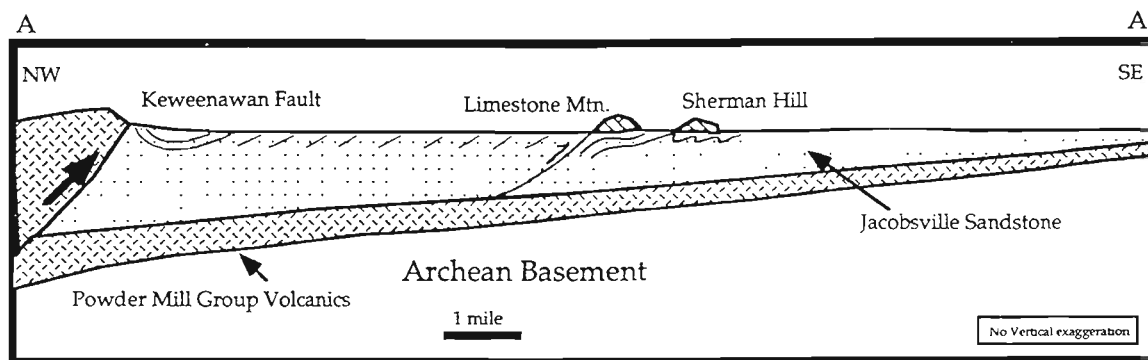


Figure 1. Cross section showing the relations of the Limestone Mountain and Sherman Hill outliers to the Keweenaw thrust and Jacobsville Sandstone.

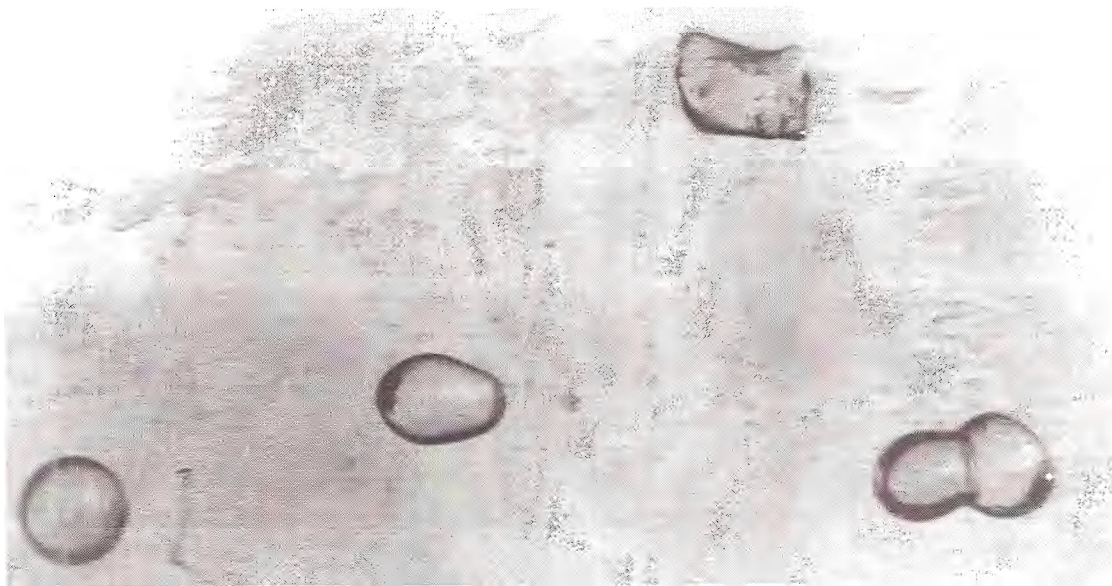


Figure 2. Microtektites from Ordovician carbonates at Limestone Mountain. Diameters are ~50 microns.

EVIDENCE OF INTERRUPTIONS DURING FRACTIONAL CRYSTALLIZATION OF THE DULUTH COMPLEX LAYERED SERIES AT DULUTH

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An important result of recent geologic mapping of the Middle Proterozoic (1099 Ma) Duluth Complex in the vicinity of Duluth has been the delineation of the cumulus stratigraphy of the layered series (see field trip 4 of this conference [hereafter FT4]). This stratigraphy is consistent with its overall formation by fractional crystallization of mafic cumulates at the floor of a 3- to 5-km-thick sheetlike tholeiitic mafic intrusion. In detail, however, the crystallization and differentiation of the layered series magma system was frequently interrupted. These interruptions are most evident in the middle part of the intrusion, termed the cyclic zone, where a general transition from Pl+Ol cumulates to Pl+Cpx+Ox±Ol cumulates occurs in a cyclic progression of at least five macrocycles (FT4, Fig. 5). The boundary between each macrocycle is marked by an abrupt regression from a Pl+Cpx+Ox±Ol cumulate back to a Pl+Ol cumulate. Within each macrocycle, the progression to more evolved cumulates is commonly marked by abrupt changes in texture and mineralogy (e.g., FT4, Fig. 7), though elsewhere the progression seems gradual. An extreme example of an abrupt change in texture is the interlayering of very fine-grained, equigranular olivine microgabbro and medium-grained gabbro (Pl+Cpx+Ox±Ol) cumulates observed in the upper parts of two macrocycles (FT4, Fig. 5). Another feature of the cyclic zone is that it marks the lower stratigraphic extent of anorthositic inclusions in the layered series (FT4, Fig. 2).

One possible interpretation of this cyclicity is that the progression of rock types within each macrocycle resulted from normal magmatic differentiation that evolved to saturation in augite and Fe-Ti oxide in addition to plagioclase and olivine, and that the regression to saturation in only plagioclase and olivine resulted from recharge of a more primitive magma. This interpretation predicts a gradual transition in cumulate rock type through each cycle with mafic phases becoming iron-enriched followed by an abrupt reversal in cumulus mineralogy and a shift to Mg-enriched compositions across macrocycle boundaries. Some cycles certainly change gradually in the texture and modal character of augite and Fe-Ti oxide, consistent with their becoming gradually saturated in a differentiating magma. However, some changes in rock type are locally very abrupt and not easily explained by magmatic recharge. For example, it is not obvious how magmatic recharge, which would have added heat to the system, could account for the very fine-grained gabbro layers just beneath the horizons of cumulus reversal (FT4, Fig. 5). Moreover, olivine and pyroxene compositions across these cycles (FT4, Figs. 5 & 7) do not vary as expected. However, it should be noted that an interpretation of mineral compositions is complicated by the uncertain effect of cumulus Fe-Ti oxide on the partitioning of FeO and MgO in mafic silicates and by the iron-enrichment effect of increased amounts of trapped liquid in the different cumulates.

An alternative cause for cyclic variations in cumulus mineralogy, texture, and mineral chemistry in the cyclic zone is decompression owing to eruption of magma to the surface. The basic effect of such a phenomenon is a lowering of the liquidus temperatures of all mineral phases. Although the Duluth Complex at Duluth was probably under a lithostatic pressure of at most 2-3 kb and perhaps as little as 1 kb, any decompression of the layered series magma in the middle stages of differentiation, when it was approaching saturation in augite and Fe-Ti oxide, could have resulted in instantaneous saturation (or over-saturation) of these phases. This may explain the formation of gabbroic cumulates in the upper parts of the macrocycles (FT4, Fig. 5). The undercooling effect of decompression could also account for the finer grained textures observed in the upper parts of the macrocycles. The effect of decompression on equilibrium mineral compositions would be a slight to negligible increase in the MgO/(MgO+FeO) ratio of mafic phases and in the An content of plagioclase. Any such effect on olivine and pyroxene compositions would be minimal compared to that of either cumulus Fe-Ti oxide crystallization or varied amounts of trapped liquid, effects which better account for the nonsystematic variation of these compositions across the cyclic zone (FT4, Fig. 5). An eruptive cause for the macrocycles is also consistent with anorthositic inclusions in the

cyclic zone, because they presumably came from rocks of the anorthositic series that capped the layered series chamber. Finally, the potential for complex eruptive events to cause rapid fluctuations in pressure can explain the abrupt changes in texture observed within individual cycles. However, it is unclear whether pressure could increase rapidly enough with the cessation of eruption to account for the abrupt cumulus reversals that mark the boundaries between cycles.

Evidence of eruption from the layered series magma chamber is also found outside the cyclic zone. The range of rock types intruded into the anorthositic series cap provides direct evidence of magmas escaping the layered series (FT4, Fig. 2). Less direct evidence is the composition of the very fine grained ferrodiorite which forms the upper "chilled" contact of the layered series with the anorthositic series. Although whole rock analyses are lacking, the presence of ilmenite, amphibole, and Fe-rich pyroxene in this fine-grained rock indicates an evolved composition that is could not have been parental to the entire layered series. This composition implies that the layered series magma was quenched against the anorthositic rocks after the magma had become significantly differentiated and at a time when the anorthositic cap would have been well heated. The quenching evident in the ferrodiorite, therefore, seems best explained by decompression undercooling. Further studies are planned to determine whether the composition of the upper contact zone ferrodiorite corresponds to that of the magmas which generated the cumulates of the cyclic zone.

The perturbations evident in the crystallization history of the layered series have important implications for its mineralization potential. Both eruptive decompression and magmatic recharge can create geochemical discontinuities that can provide traps for mineralizing solutions. A zone of sulfide enrichment is one such trap that seems to be important in localizing PGE in layered intrusions (Boudreau and McCallum, 1992). In the case of eruption, depressurization lowers the solubility of sulfur in silicate magma and results in increased exsolution of sulfide melt. Depending on the compositions of the resident and replenishing magma, magma recharge and mixing also can produce hybrid rocks enriched in sulfide.

Boudreau, A.E., and McCallum, I.S., 1992, Concentration of platinum-group elements by magmatic fluids in layered intrusions: *Economic Geology*, v. 87, p.1830-1848.

MOVEMENT OF Ti ACROSS THE DULUTH COMPLEX-BIWABIK IRON FORMATION
CONTACT AT DUNKA PIT, MESABI IRON RANGE, NORTHEASTERN MINNESOTA

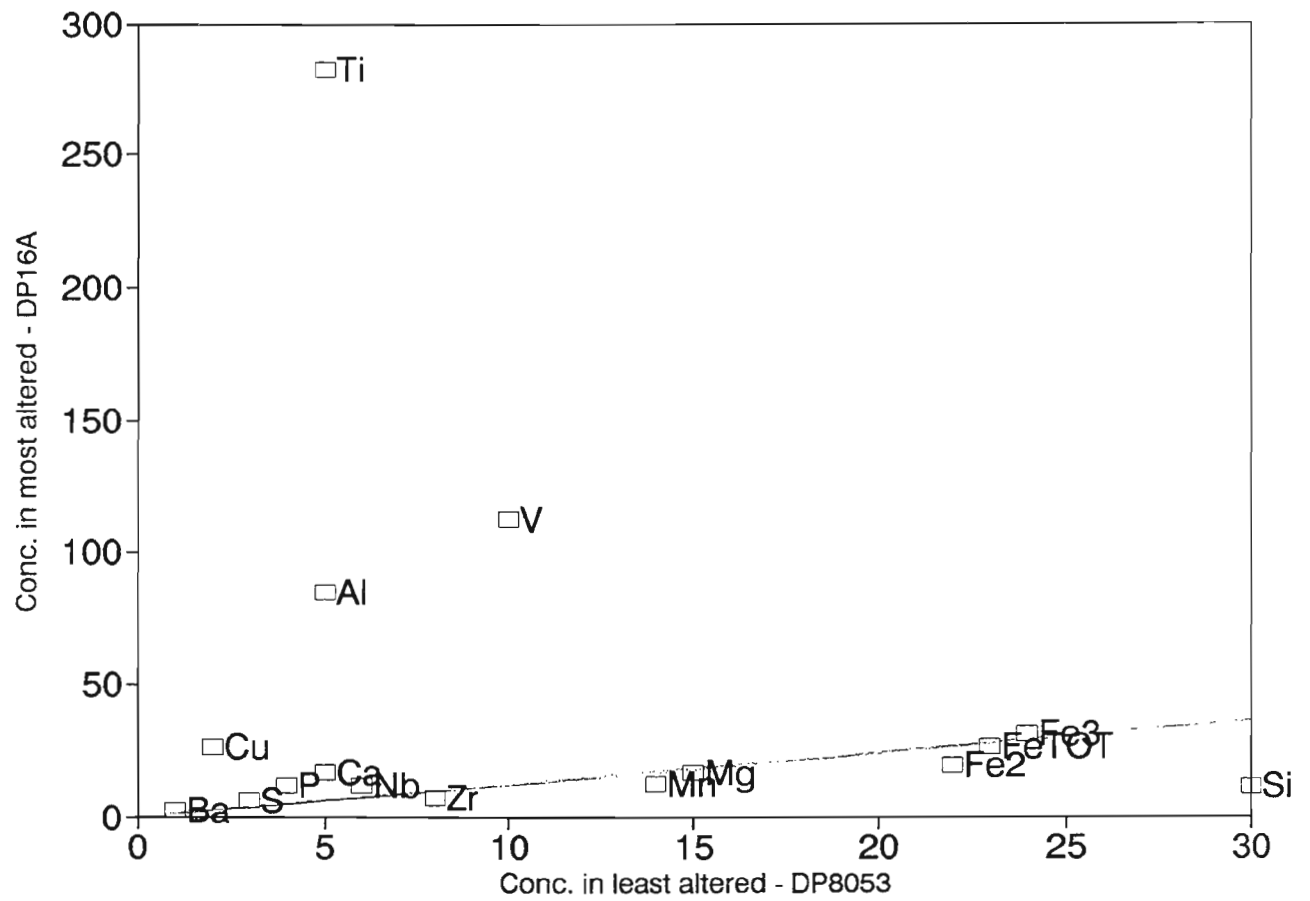
MUHICH, Thomas G., Geology Dept., University of Minnesota-
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The Biwabik Iron Formation(BIF) in the Dunka Pit area has shown in preliminary investigations to have higher than normal Ti concentrations. The higher Ti concentrations occur only where the iron formation is in contact with the Duluth Complex, a 1.1 Ga gabbroic intrusion, and are believed to be related to metasomatism. Metasomatic transfer of Ti is of particular interest as it is normally an immobile element. The increased Ti content of the BIF also decreases the amount of extractable Fe in the iron ore.

Weight percent titania from a typical whole rock geochemical analysis for an altered slaty BIF is 3.96, as compared to a value of 0.07 from unaffected "normal" slaty iron formation. The whole rock geochemistry also shows an increase in several common oxides and trace elements, with up to 4.60 wt. % Al_2O_3 , 1.97 wt.% CaO, and 393 ppm V. These values can be explained by the heterogeneity of the iron formation and the variation of degree of metasomatism in the area near the contact with the Duluth Complex.

Isocon plots constructed from whole rock data indicated an overall gain of Ti, Al and V to the iron formation (FIG.1). Comparison of the composition of an unaltered iron formation sample (DP8053) more distant from the contact with the Duluth Complex with an altered iron formation sample (DP16A) from near the contact with the Duluth Complex yielded Ca/Co (concentration in altered rock divided by concentration in unaltered rock) values of 17.04 for Al; and 56.57 for Ti. These values indicate a high enrichment in these elements. Field and petrographic observations showing cores of magnetite layers in the iron formation being replaced by ilmenite support the metasomatic origin of the increased Ti and V. Layers of plagioclase and pyroxenes between layers of titanomagnetite in the iron formation at the contact possibly support the metasomatic origin of increased Ca and Al.

FIG.1: ISOCON PLOT of DP16A vs. DP8053



GEOCHEMICAL EXPLORATION FOR BASE AND PRECIOUS METALS USING GLACIAL TILL

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Exploration in the Superior Province of Canada and the United States has to contend with problems posed by glacial overburden and recent activity has centered largely on the search for gold deposits. In many areas exploration has been based on the sampling of tills, frequently by deep overburden drilling, and analysis of heavy mineral concentrates. Notwithstanding the role that till geochemistry has played in the discovery of some important gold deposits over the last few years, increased appreciation of the nature of the glacial history and stratigraphy and the character of gold within till has led to the recognition of a number of ways whereby the effectiveness of exploration can be improved upon.

In order for till geochemistry to be useful in exploration, a number of conditions must be fulfilled, including:

1. mineralization or alteration halo related to mineralization subcropping at the bedrock/overburden interface;
2. glacial erosion and dispersal of a recognizable signature of mineralization into the glacial sediments;
3. preservation of glacial sediments containing this geochemical component (trace metal or mineral) at positions subsequently selected for sampling (normally drill sites);
4. correct identification of specific till units and associated ice movement history;
5. collection of adequately large and representative samples;
6. appropriate sample preparation and processing;
7. appropriate geochemical analyses; and
8. correct data processing and interpretation.

While we have no control over the first two geological conditions, and only limited control over till availability, we can control the quality and thoroughness of sampling, sample identification, sample preparation, analysis and interpretation. In particular, attention needs to be focused on obtaining a large enough sample to be adequately representative, together with appropriate sample processing, analysis, data processing and interpretation.

In the course of recent exploration by the Minnesota Department of Natural Resources in areas of very low geological outcrop and thick and complex glacial overburden, particular attention has been given to understanding the Quaternary overburden and at the same time searching for indications of mineralization, particularly for gold.

With respect to geochemical exploration, approaches adopted have involved the multi-element analysis of heavy mineral concentrates and the fine fraction of glacial tills. Initial consideration of the data reveals the existence of some anomalous concentrations suggestive of mineralization. Continued evaluation of the data has drawn attention to potentially more meaningful procedures for data presentation in terms of reflecting mineralization.

On the basis of favorable geology, level of exploration activity to date and results indicated, certain areas clearly merit further exploration.

DIMENSION STONE INVENTORY OF NORTHERN MINNESOTA

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A dimension stone inventory is currently being conducted on state lands in northern Minnesota and federal lands in the Superior National Forest. The purpose of this inventory is to identify areas of crystalline rock that exhibit potential for quarrying and encourage the stone industry to further evaluate the prospects. The ultimate goal is the opening of new quarries within the state.

A report entitled Dimension Stone Inventory of Northern Minnesota is available. This report summarizes the first two years of the inventory. New prospect site information is open-filed and available for distribution as the inventory progresses. To date, fifteen prospects have been identified. Prospects have been identified in the Duluth Complex, Vermilion Granitic Complex, and Late Archean granitoid rocks. Outcrops are evaluated with respect to joint spacings, color, texture, deleterious minerals, and potential block size.

As a result of the first two years of the inventory, three quarry prospect sale areas offered by the USDA Forest Service have been acquired by Cold Spring Granite Company.

A color brochure entitled Minnesota Granite has been published in conjunction with the Superior National Forest. It contains photographs of polished tiles from selected prospects.

Polished tiles from each prospect site are available for inspection at the DNR Minerals offices and the Superior National Forest office in Duluth.

EXPLORATION AND MINING ACTIVITY IN NORTHWESTERN ONTARIO

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The mineral sector in Ontario provided an estimated 19,700 direct jobs and produced products with a total Canadian dollar value of \$4.8 billion in 1992.

Four of the top gold producers in Canada in 1992 were from northwestern Ontario: Williams Mine (496,920 oz), Golden Giant Mine (451,403 oz), Campbell Mine (298,875 oz) and the David Bell Mine (210,121 oz).

This poster displays the producing mines and advanced mineral exploration projects in the northwestern portion of the Province of Ontario. Currently there are 7 producing gold mines, 2 base metal mines, 6 quarries, 5 amethyst mines and 10 amethyst producers in the region employing approximately 3160 people. Quarry development consists of 2 dimension stone, 1 crushed granite, 1 quartz, 1 diabase, and 1 horticultural peat moss producer. There are also 5 projects in the advanced exploration stage. Representative ore samples of Northwestern Ontario are on display.

A statistical summary booklet that tabulates regional data such as reserves, grades, location, ownership and development is available free of charge. Many other free brochures are also available.

SEDIMENTOLOGY AND PROVENANCE OF THE EARLY PROTEROZOIC MICHIGAMME FORMATION AND GOODRICH QUARTZITE, NORTHERN MICHIGAN: REGIONAL STRATIGRAPHIC IMPLICATIONS AND SUGGESTED CORRELATIONS

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The Early Proterozoic Michigamme Formation was deposited in the southeastern part of the Animikie basin. It conformably overlies the Goodrich Quartzite and comprises three widespread members--an informal lower member of thin-bedded shale, siltstone, and sandstone; the Bijiki Iron-formation Member, and an informal upper member of turbiditic graywacke, siltstone, and mudstone. The Goodrich is interpreted as having been deposited in a tidally-influenced marine environment. The lower member of the Michigamme is interpreted as having been deposited in a tidally-influenced environment, the iron-formation member below wave base in somewhat deeper water, and the upper member in still deeper water via turbidity currents and suspension settling. The Dead River, Clark Creek, East Baraga and Gwinn basins are down-folded and down-faulted remnants of the widespread Michigamme sequence.

Paleocurrents and petrography indicate that the Goodrich Quartzite was locally derived from the Archean northern complex. Several lines of evidence, including paleocurrents, paleogeographic setting and Nd isotopes (Barovich et al., 1989), suggest that the graywacke of the southern portion of the outcrop area was derived from the south (Early Proterozoic Wisconsin magmatic terranes, Archean miniplates, and Early Proterozoic sedimentary units formed on the continental margin), and that the graywacke in the northern area was derived from Archean terrane to the north. Paleocurrent indicators in the Rove Formation north of Lake Superior are toward the south (Morey, 1967). Any reconstruction must allow for the spreading during the formation of the 1,100 Ma Midcontinent rift system. If the regional paleogeography is restored to its pre-rift position by moving the block southeast of the Midcontinent rift system a distance of 100 km to the northwest (perpendicular to the trend of the rift), the distance between the northern Michigamme and the southernmost Rove is reduced to 65 to 100 km. It seems probable that the fine-grained northern Michigamme is "distal Rove Formation" deposited on the distal portion of a southward-thinning submarine fan or on the basin plain.

The tectonic model that best fits the data is a northward-migrating foreland basin as proposed by Hoffman (1987) and in E-C Minnesota by Southwick and Morey (1991) and Holst (1991). The fold-and-thrust belt to the south of the basin was comprised of the aforementioned rock units and the peripheral bulge to the north was comprised of Archean granites and greenstone belt rocks.

This study has raised stratigraphic questions that challenge some long-accepted correlations (Morey and Van Schmus, 1988; revised correlations seem to be required. The stratigraphy in outcrop and drill core in the western Marquette district is similar to that on the Gogebic range which is located 120km to the west-southwest and is on depositional and tectonic strike. On the Gogebic, the relevant units are the Palms Formation, the Ironwood Iron-formation, and the Tyler and Copps Formations; the interpreted depositional environments (Ojakangas, 1983) are also similar. These units were likely deposited at the same time in the northward-transgressing Early Proterozoic sea. The proposed correlations between the Gogebic and the western Marquette are as follows:

Gogebic Range	Western Marquette Range
Tyler and Copps Formations	Upper slate member, Michigamme Formation
Ironwood Iron-formation	Bijiki Iron-formation Member, Michigamme Formation
Palms Formation	Lower slate member, Michigamme Formation Goodrich Quartzite

The stratigraphic sequences to the north on the Gunflint and Mesabi ranges are similar to those on the Gogebic range and the western Marquette range. Correlations can be made, on one hand, between the western Marquette range and the Gogebic range, and on the other hand, between the Mesabi and Gunflint ranges. Lithologic correlations also can be made between all four of these ranges, but diachronous relationships between the western Marquette and Gogebic ranges to the south and the Mesabi and Gunflint ranges to the north are required. If the model of a northward-migrating foreland basin is utilized, with the basal terrigenous clastic units and the iron-formations deposited on the peripheral bulge and the turbidite sequences deposited both on the bulge and in the deeper parts of the foreland basin, the Michigan units were deposited prior to deposition of the northerly units. If it is instead assumed that the basal terrigenous clastic units and the iron-formations were deposited on a stable shelf prior to the development of the foreland basin with its turbidite fill, northward-migrating depositional environments were also probable. In both models, it can be assumed that the terrigenous clastic units and the overlying iron-formations form essentially continuous sheet-like deposits across the basin, between Michigan-Wisconsin and Minnesota-Ontario.

NOTE: This work was accomplished while on WAE status with the U.S. Geological Survey.

References

- Barovich, K.M., Patchett, P.J., Peterman, Z.E., and Sims, P.K., 1989, Nd isotopes and the origin of 1.9-1.7 Ga Penocean continental crust of the Lake Superior region: *Geological Society of America Bulletin*, v. 101, p. 333-338.
- Hoffman, P.F., 1987, Early Proterozoic foredeeps, foredeep magmatism, and Superior-type iron-formations of the Canadian Shield, in Kroner, A., ed., *Proterozoic Lithospheric Evolution*, Geodynamic Series, American Geophysical Union, v. 17, p. 85-98.
- Holst, T.B., 1991, The Penocean orogeny in Minnesota and Upper Michigan -- A comparison of structural geology: In Sims, P.K. and Carter, L.M.H., eds., *Contributions to Precambrian Geology of the Lake Superior Region*: U.S. Geological Survey Bulletin 1904-D, 10 p.
- Morey, G.B., 1967, Stratigraphy and sedimentology of the Middle Precambrian Rove Formation in northeastern Minnesota: *Journal of Sedimentary Petrology*, v. 37, p. 1154-1162.
- Morey, G.B. and Van Schmus, W.R., 1988, Correlation of Precambrian rocks of the Lake Superior region, United States: U.S. Geological Survey Professional Paper 1241-F, 31 p.
- Ojakangas, R.W., 1983, Tidal deposits in the early Proterozoic basin of the Lake Superior region -- The Palms and the Pokegama Formations; Evidence for subtidal-shelf deposition of Superior-type banded iron-formation: in Medaris, L.G., Jr., ed., *Early Proterozoic Geology of the Lake Superior Region*: Geological Society of America Memoir 160, p. 49-66.
- _____, In Press, Sedimentology and provenance of the Early Proterozoic Michigamme Formation and Goodrich Quartzite, Northern Michigan -- Regional stratigraphic implications and suggested correlations: In Sims, P.K. and Carter, L.M.H., eds., *Contributions to Precambrian Geology of the Lake Superior Region*: U.S. Geological Survey Bulletin 1904-R.
- Southwick, D.L. and Morey, G.B., 1991, Tectonic imbrication and foredeep development in the Penocean orogen, east-central Minnesota - An interpretation based on regional geophysics and results of test drilling: In Sims, P.K. and Carter, L.M.H., eds., *Contributions to Precambrian Geology of the Lake Superior Region*: U.S. Geological Survey Bulletin 1904-C, 17 p.

KITTSOON COUNTY BLOATING CLAYS

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Glacial Lake Agassiz clays from Kittson County in northwestern Minnesota exhibit a characteristic spherical bloating habit when fired to $\sim 2,100^{\circ}\text{F}$. The bloating characteristics were identified in 1989 during a regional study of the characteristics of Minnesota's clay resources. Extruded briquets of Brenna Formation material (collected in 1985 by the USBM) bloat spheroidally even when fired to relatively low temperatures. Further research confirms the highly expanding spherical nature of the clays, in both processed (crushed to -50 mesh) and raw clay form. Current research has determined that the clays can be rotary kiln fired. The resulting fired product is suitable for lightweight aggregate in structural concrete, meeting the requirements of ASTM C 330 standard specifications. The processing and pelletizing characteristics of the Kittson clays are presently being studied. This study demonstrates that the Kittson clays can be processed, extruded, cut into pellet form, and fired to produce a lightweight, highly expanded, uniformly sized, near-spherical product with a moisture absorption resistant shell.

The Kittson clays consist of clay and silt (rock flour) deposited in Pleistocene Glacial Lake Agassiz. The bloating clays occur in the Sherack (alluvial clays - locally bloat) and Brenna (glacial lake clays) Formations. These clays are widespread and flat-lying and within 0-30 feet of the surface. The maximum thickness tested is about 75 feet with the optimum range for the best expanded material being about 25 feet thick at an average depth of 25 feet. Bulk X-ray mineralogy indicates that the expanding clays consist of quartz with minor kaolinite, illite, and smectite and trace amounts of feldspar and carbonate.

Bloating temperature ranges from $1,900^{\circ}\text{F}$ to $2,200^{\circ}\text{F}$, and fired product bulk density ranges from 16.5 lb/ft^3 to 33 lb/ft^3 depending on processing method and desired end product. Lower bulk density is associated with higher firing temperature. Specific gravity of the rotary kiln processed clays is 1.1 gm/cm^3 , while water absorption is 11.1% at four hours. Upper portions of the Brenna Formation expand up to 300% on firing.

Potential use of the Kittson clays lies in their expanded state. Rotary kiln processing of the dried, raw clay will produce lightweight aggregate suitable for structural concrete, lightweight fill, and landscaping material. Further processing of the dried, raw clay, e.g., crushing, screening, wetting, extruding, firing, will produce a uniform, spheroidal aggregate with potential for use in insulating concrete, as a filler, and as a substitute for perlite in horticultural growing mixes. Firing the dry, finely-ground clay produces a lightweight foam, which may have potential as a natural substitute for polystyrene in some applications.

OUTLYING MISSISSIPPI VALLEY-TYPE SULFIDE MINERALIZATION, FILLMORE COUNTY, MINNESOTA.

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A sulfide-rich mineralized zone in the Lower Ordovician Oneota Dolomite was recently discovered in a quarry in Fillmore, Co., Minnesota. This is the northernmost known occurrence of carbonate-hosted mineralization that is similar in paragenetic sequence and wall-rock alteration to the classic deposits in the main Upper Mississippi Valley (UMV) mining district. Mineralization is stratiform and appears to be restricted to an algal reef facies at least 4 m thick and over 60 m in diameter. The top of the deposit lies about 5 m below a regional unconformity that separates the Oneota Dolomite from the overlying Shakopee Formation. Most of the mineralization consists of the sulfides marcasite and pyrite, with a lesser amount of calcite and quartz. The sulfides occur as vein fillings in narrow fractures, along the laminae of algal domes and mats, as cavity fillings in vugs and brecciated zones, and possibly as disseminations by replacement. Many cavity fillings are symmetrically banded, with sulfides lining the outside of cavities and calcite filling the center.

This deposit lies along the axis of the northern part of the Allamakee (Mineral Point) anticline, a northwestward-trending anticline that is associated with several mines within and in the fringes of the main UMV mining district in Iowa and Wisconsin. The genesis of this stratiform body may be related both to its position on the anticline and to the abundance of algal features, which locally enhanced porosity compared to less porous, massive Oneota Dolomite elsewhere in the area.

Although preliminary assays of samples from this deposit show only slightly anomalous Pb, Cu and Zn values, many features typical of mined deposits to the south indicate potential for the discovery of economic orebodies in Minnesota. Because it is an outlying deposit far from the postulated source of ore-bearing fluids responsible for UMV mineralization, additional study may also yield important information concerning the regional genesis of these orebodies.

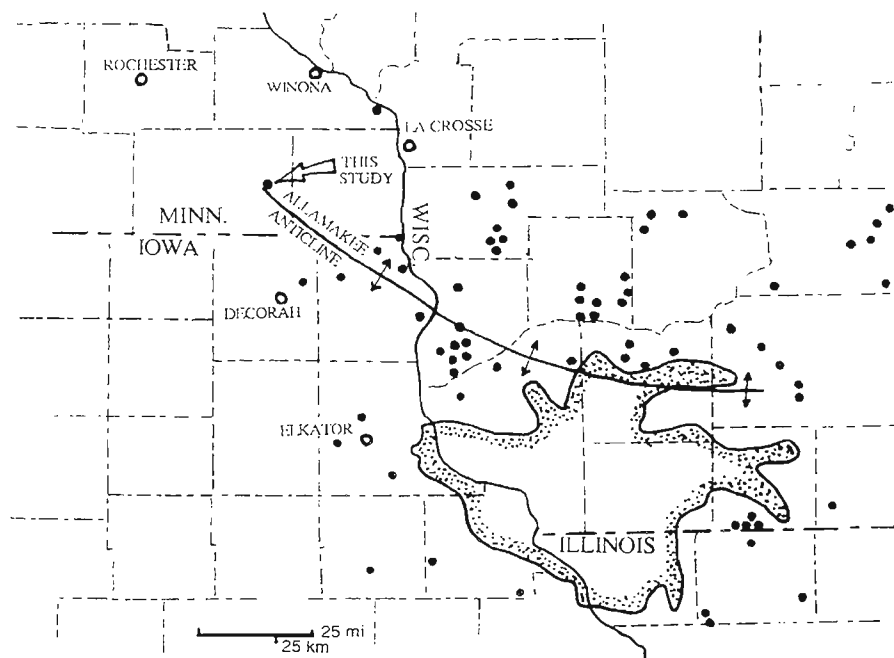


Figure 1. Mineral deposits and occurrences north of the main Upper Mississippi Valley mineral districts. Stippled outline encloses principal past productive areas. Dots denote mineral occurrences, prospects, or productive mines. Modified from Heyl and West (1982).

NATURE AND AGE OF THE VERMILION FAULT SYSTEM, NORTHERN MINNESOTA

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The Vermilion Fault is a prominent right lateral wrench system that trends northwesterly across northern Minnesota. It is terminated at its eastern end by the Duluth Gabbro Complex and extends across Archean terrane to at least the North Dakota border. The fault system consists of a single strand in its western portion and three strands in its eastern portion: the Vermilion, Dark River, and Silverdale Faults. These three strands join in eastern Koochiching County.

Matching geologic units on each side of the Vermilion Fault in the western portion indicate a displacement of about 23 miles. Measurements between matching units on the eastern portion is more nebulous, but the Vermilion strand appears to have 11 to 12 miles of displacement, the Silverdale strand 8 to 9 miles, and the Dark River strand 1 to 2 miles. These add up to about the 23 mile displacement in the western portion.

The Kabetogema-Kenora dike swarm is cut by the Vermilion Fault system and matching dikes on opposing sides in the western portion also yields displacement of about 23 miles. The fault system is therefore at least younger than very late Archean or early Proterozoic age. The Dark River Strand is continuous with the Biwabik fault which cuts the Biwabik Iron Formation and the Virginia Formation, indicating that at least that strand is of post-Penokean age.

A Keweenawan age of the Vermilion Fault system is suggested. The system is interpreted to be a transform fault system that accommodated some of the opening of the Midcontinent Rift in northern Minnesota.

IGNEOUS STRATIGRAPHY OF THE PARTRIDGE RIVER AND SOUTH KAWISHIWI INTRUSIONS - DULUTH COMPLEX, NORTHEASTERN MINNESOTA

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The Duluth Complex is a composite series of tholeiitic intrusions of Keweenaw age (1.1 b.y.) that formed with associated basaltic volcanism along a portion of the Mid-continent Rift. Rocks that are footwall to the Complex include the Middle Precambrian Virginia Formation (argillite and graywacke), Biwabik Iron-formation (BIF), and Early Precambrian granitic rocks of the Giants Range Batholith. Hangingwall rocks are generally basalts of the North Shore Volcanic Group (Keweenaw). Emplacement of multiple subintrusions, which collectively make up the Complex, occurred during an episode of extensional tectonism which produced the Mid-continent Rift. Two of these smaller subintrusions have been extensively drilled for Cu-Ni deposits (Fig. 1); they are informally named the Partridge River and South Kawishiwi intrusions (PRI and SKI, respectively). During the last six years, 550 drill holes (634,000 ft. of drill core) have been relogged in these two intrusions by: Geerts, 1991; Hauck, in prep.; Severson and Hauck, 1990; Severson, 1991; Severson, in prep.; and Zanko and Severson, in prep.

The Partridge River Troctolite Series (PRTS) consists of at least seven major igneous units which are correlatable in drill holes over an indicated 15-mile strike length. From the base up, these units are characterized by: Unit I - sulfide-bearing heterogeneous mix of augite troctolite and troctolite with minor discontinuous ultramafic horizons; Unit II - homogeneous-textured troctolite, with abundant ultramafic horizons in the Wetlegs area; Unit III - mottled-textured, fine-grained, anorthositic troctolite exhibiting a highly irregular olivine oikocryst distribution (major "marker horizon"); Unit IV - augite troctolite (homogeneous) with a fairly persistent basal ultramafic horizon (termed " $\pm$ picrite" in the Babbitt area); Unit V - coarse-grained anorthositic troctolite (homogeneous) that grades downward into Unit IV; and Units VI and VII - homogeneous troctolite to anorthositic troctolite, each with a persistent ultramafic base.

Most of the upper units (III through VII) represent single cooling units in that they are floored by persistent ultramafic horizons. Whereas, other units (I and II) near the footwall are indicative of rapid magma replenishment and magma contamination due to assimilation of the footwall rocks. Though age relationships are uncertain, Unit I appears to have been intruded earliest along bedding planes of the Virg. Fm into a progressively developing magma chamber (abundant inclusions and heterogeneous nature), while the more homogeneous Units III through VII appear to have been emplaced into a well-developed magma chamber. The persistent ultramafic horizons of the upper units probably represent the inception of episodic magma injection that crystallized more primitive ultramafic layers before mixing with the resident magma.

The PRTS is cut by later plugs and vertical bodies of Oxide-bearing Ultramafic Intrusions (OUIs). The OUIs are characterized by coarse-grained to pegmatitic pyroxenite, peridotite, and dunite, most of which contain thick lenses of massive oxide. Some of the bodies exhibit a crude zonation consisting of a olivine-rich core and pyroxenite rim (e.g., Longnose and Section 17 Fe-Ti deposits). In almost all cases the OUIs are situated along linear zones that correspond to known structural discontinuities present at the basal contact of the Complex, which suggests that faulting was important to OUI formation. At several localities, a genetic link between iron-formation assimilation and OUI formation is apparent. Several near-vertical, pyroxenite-hornblende-granitic/granophyric veins intrude the troctolitic rocks along the eastern margin of the Babbitt deposit. Spatially, these late veins are present in drill holes along a north-south zone situated between the Partridge River and South Kawishiwi intrusions. This same zone corresponds to major north-trending normal fault (down to the east). Because this fault has abundant associated late granophyric (etc.) veins that occur along its strike length, it has been informally designated as the Grano-Fault (Fig. 1).

An entirely different igneous package is present within the South Kawishiwi Troctolite Series (SKTS). At least 12 different mega-units occur within the South Kawishiwi intrusion; however, only alternating portions of the entire stratigraphic package are present within each of the drilled Cu-Ni deposit areas of the SKI. A generalized section of correlative igneous units present within the SKTS over a 19-mile strike length is presented. From the base up, the units of the SKTS are designated as: BAN - Bottom Augite troctolite and Norite zone (sulfide-bearing, with local inclusions of BIF and Giants Range granite); BH - Basal Heterogeneous zone (sulfide-bearing) = heterogeneous mix of troctolite and anorthositic troctolite; U3 - Ultramafic 3 = package of alternating layers of ultramafic and troctolitic rocks (often contains massive oxide horizons and/or BIF inclusions); PEG - Pegmatitic unit of Foose (1984) = poorly-defined unit where pegmatoids and pegmatite zones are commonly, but not necessarily, present; U2 - Ultramafic 2 = package of alternating layers of ultramafic and troctolitic rocks (massive oxide layers are only rarely present); AT-T - Anorthositic Troctolite to Troctolite zone; U1 - Ultramafic 1 = package of alternating layers of ultramafic and troctolitic rocks; UW - Updip Wedge = package of heterogeneous sulfide-bearing troctolites present only at the Dunka Pit area; MAIN AGT - delineated by a zone where augite troctolite (AGT) is the dominant rock type; AT-T - thick monotonous zone of anorthositic troctolite and troctolite; AT (T) = thick monotonous zone of anorthositic troctolite to troctolitic anorthosite; and Highway One Corridor Rocks (AN-G Group, and Upper AGT) = a thick igneous sequence of alternating anorthositic and gabbroic rocks present within five deep drill holes (4000-5200 feet deep) in the "Highway One Corridor" area. (It is impossible to determine if the AN-G GROUP rocks can be correlated with the Anorthositic Series of the Duluth Complex.)

Unlike the Partridge River intrusion, the units of the South Kawishiwi intrusion do not represent individual "cooling units." Rather, the SKI units only represent zones where one particular rock type, or a package of rock types, is predominant (i.e., augite troctolite is dominant in the MAIN AGT). While these units are not cooling units, they are indicative of changes in the magma chamber that reflect either: 1) that crystallization occurred during periods of repeated magma injection (i.e., the U1, U2, and U3 units); 2) that crystallization proceeded uninterrupted to produce augite troctolite zones (i.e., the MAIN AGT); or 3) contamination of the magma occurred due to assimilation of the footwall rocks (i.e., BAN and U3-massive oxide units).

Only a few of the above described units are present throughout all the SKI. Because the specific units occur sporadically throughout the SKTS, determination of the age of one unit relative to another unit is severely hampered. This is also complicated by the overall stratigraphic pattern, which indicates that the SKI is not only "layered" vertically, but is also "compartmentalized" horizontally along its strike length. In other words, the SKI is itself a multiple intrusion in which each of the individual units exhibit a finite spatial extent, and each of the units overlap each other in a myriad of patterns.

References:

- Foose, M. P., 1984, Log and correlation of drill holes within the South Kawishiwi intrusion, Duluth Complex, northeastern Minnesota: U.S. Geol. Survey, Open-file Rept. 84-14.
- Geerts, S. D., 1991, Geology, stratigraphy, and mineralization of the Dunka Road Cu-Ni prospect, northeastern Minnesota: Nat. Res. Research Inst., Univ. Minn., Duluth, Tech. Rept., NRRI/TR-91/14, 59 p.
- Hauck, S. A., in prep., Geology and mineralization of the Bathtub Cu-Ni area, Minnamax Cu-Ni deposit: Nat. Res. Research Inst., Univ. Minn., Tech. Rept.
- Severson, M. J., and Hauck, S. A., 1990, Geology, geochemistry, and stratigraphy of a portion of the Partridge River intrusion: Nat. Res. Research Inst., Univ. Minn., Tech. Rept., NRRI/GMIN-TR-89-11, 235 p.
- Severson, M. J., 1991, Geology, mineralization, and geostatistics of the Minnamax/Babbitt Cu-Ni deposit (Local Boy area), Minnesota, Part I: Geology: Nat. Res. Research Inst., Univ. Minn., Duluth, Tech. Rept., NRRI/TR-91-13a, 96 p.
- Severson, M. J., in prep., Igneous stratigraphy of the South Kawishiwi intrusion, Duluth Complex, northeastern Minnesota: Nat. Res. Research Inst., Univ. Minn., Duluth, Tech. Rept.
- Zanko, L. M., and Severson, M. J., in prep., Geology and mineralization of the Serpentine Cu-Ni area, Minnamax Cu-Ni deposit: Nat. Res. Research Inst., Univ. Minn., Duluth, Tech. Rept.

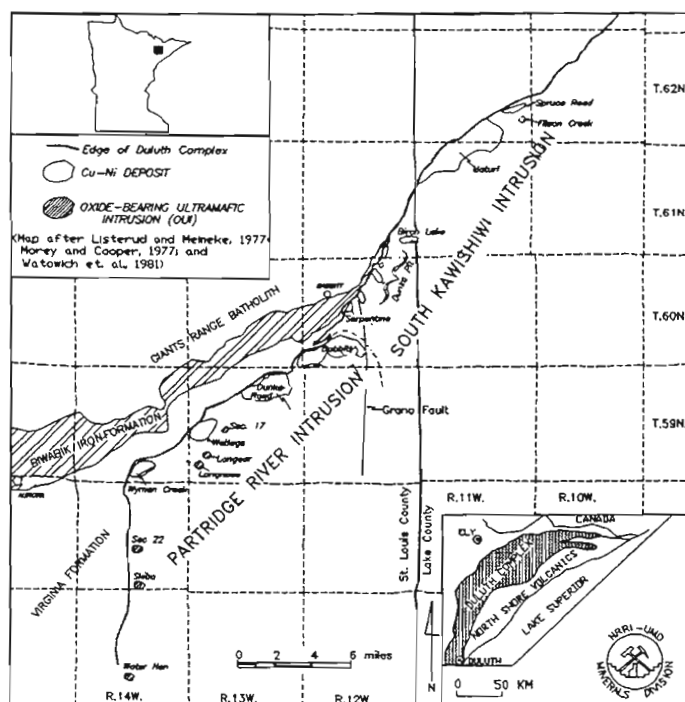


Figure 1: Location map of Cu-Ni and Fe-Ti deposits within the Partridge River and South Kawishiwi intrusions, Duluth Complex, northeastern Minnesota.

PRELIMINARY INVESTIGATIONS OF THE NICOPOR COPPER-NICKEL
PROSPECT, NORTHWESTERN ONTARIO

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The Nicopor copper-nickel prospect occurs at the northern contact of the Archean Schreiber greenstone belt with the Crosman Lake granitic batholith. The greenstone belt assemblage consists of an east-trending, homoclinal succession of mafic to felsic metavolcanic rocks intruded by sill-like gabbro bodies. Base metal sulphides occur as massive to vein-like and net-textured aggregates in a narrow, linear zone that follows the contact between a massive amphibolite (melagabbro) on the south and medium-grained, equigranular, micrographic granite on the north and is exposed over a distance of approximately 75 m. The sulphide zone on surface ranges up to approximately 2 m in width and rapidly grades outwards into disseminated mineralization in both the gabbro and granite. Diamond drilling has intersected the zone at depths in excess of 180 m. The sulphide zone is crosscut by barren aplite, syenite and feldspar porphyry dykes.

The sulphide zone consists mainly of semi-massive, net-like veinlets of pyrrhotite, pentlandite, with minor chalcopyrite, magnetite and isolated porphyroblasts of pyrite. Anastomosing sulphide veins and massive sulphides are apparently hosted mainly by brecciated granite. Sulphides within the gabbro and in the granite away from the main mineralized zone tend to be fine-grained, disseminated to blebby grains. The occurrence of native copper is noteworthy in that it occurs as small, disseminated grains within granite, apparently as a hypogene, rather than a supergene mineral.

Lithologic relationships and petrographic associations suggest that the metals and sulphur were most likely derived from the gabbroic rocks during intrusion of the granite. Sulphides were perhaps remobilized, reconcentrated and precipitated as veins and breccia fillings at or near the intrusive contact. Hydrothermal fluids generated by the granitic magma may have facilitated sulphide dissolution and remobilization.

BEDROCK GEOLOGY IN THE SHEPHARD AREA DEDUCED FROM GEOPHYSICAL DATA; IMPLICATIONS FOR MINERALS EXPLORATION

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The Shephard Project Area includes 20 townships located in east central Minnesota, adjacent to Mille Lacs. Aeromagnetic, ground magnetic and gravity data together with all available drill hole data and physical property measurements were used to infer the Precambrian geology of this area.

Precambrian Lithology

Two major greenstone belts were resolved, separated by non-magnetic metasedimentary intervals. The belts are deformed largely into synclinal structures that, according to modeling, range from 4000 to as much as 16,000 feet thick.

One of the belts is offset by a domal feature; the Mille Lacs Feature, which may be composed of older basement rocks that have been extensively granitized.

Archean (?) metamorphic rocks that constitute the southern third of the area are distinguished by relatively high densities. These rocks have been intruded by a group of granodioritic plutons.

Vigorous magnetic anomalies are observed over iron formation of the Cuyuna district.

Overburden Thickness

Magnetic depth determinations vary from less than 100 to over 500 feet. In about 30-40% of the area, Precambrian rocks are mantled by less than 200 feet of overburden. A magnetic basement depression 2000 to 3000 feet in depth, is outlined in the central part of the area. It is possible that sedimentary rocks much older in age than Quaternary, were deposited in this depression.

Mineral Potential

A number of prospects for uranium, precious metal (gold), as well as base-metal sulfide mineralization (copper, zine) are implied by these results:

-gold vein type and possibly uranium mineralization may be favoured in four target areas that involve major unconformities and structural breaks.

-massive sulfide (copper/zinc) mineralization may be involved in some of the 17 sites which involve increased magnetization.

PRECIOUS-METAL CONTENT AND TEXTURAL FEATURES OF NATIVE COPPER AND COPPER ARTIFACTS FROM THE GREAT LAKES REGION

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The ancient exploitation of native copper deposits for metalworking in North America has now been dated to at least 7,000 years before the present (Beukens et al., 1992). Although no other sources rival the Superior region, occurrences of native copper are widely distributed across the continent (Rapp et al., 1990). The possibility of using the chemistry of minor and trace elements in the native metal to constrain the provenance of particular artifacts has been explored for many years, using analytical methods such as emission spectrography, x-ray fluorescence, atomic absorption spectrometry and instrumental neutron activation analysis (INAA), an early example being the survey of Friedman et al. (1966). INAA in particular can provide data for discriminant plots by which native copper can be separated from smelted copper, imported from Europe (Hancock et al., 1991). The present study combines geological, geochemical, metallographic and mineralogical data to better (a) describe the chemical variations among native coppers and (b) constrain the origins of copper artifacts in eastern North America.

Geology of Copper Deposits:

The world-class native copper of the Superior region is associated with the late Proterozoic, Keweenawan, Midcontinent Rift, most notably in the White Pine district of upstate Michigan. Mineral deposit types within the Rift include (1) native Cu in basalts and interflow sediments, (2) sediment-hosted Cu sulphide and native Cu, (3) Cu sulphide veins in rift-related volcanics and sediments, and (4) polymetallic veins in nearby Archean country rocks (Nicholson et al., 1992). S is scarce in Rift strata, and native metal deposits relatively abundant. There is still debate over the precise (syngenetic versus diagenetic) origin of the primary White Pine ores (Seasor and Brown, 1989; Brown, 1992). Remobilization of primary, stratiform, sediment-hosted Cu deposits resulted in local enrichments associated with late faulting, occurring in high-angle and bedding-parallel veins and veinlets (Mauk et al., 1992), with local deposition of notably coarse copper. Cu occurs as the native metal, sulphides and arsenides.

Copper Chemistry:

The precious-metal contents of 11 copper artifacts have been measured by the technique of Accelerator Mass Spectrometry (AMS). Six smelted and five native coppers, all distinguishable by optical means, can be separated by their Ag and Au contents, as previously shown by INAA (Hancock et al., 1991). Because the latter technique is more cost-effective for key elements (As, Sb, Ag and Au) it remains the method of choice for large suites of samples. Variable (from ppm to percent) arsenic content is well documented in native and smelted copper (Hancock et al., 1991). The principal advantages of AMS over INAA and other bulk techniques is that (1) it is an in-situ method, analysing target areas ≤ 1 mm in size on highly-polished samples (Wilson et al., 1991), while (2) achieving much greater sensitivity for some elements in small samples (e.g., detection levels of ≈ 0.005 ppb for Au, 0.05 ppb Ag, and 0.10 ppb Pt in 100 seconds). The key result, that all smelted samples contain 1-3 orders of magnitude more Au than native Cu samples (mostly 1-10 ppm in smelted Cu, compared to ppb levels in native Cu), is perfectly clear-cut. Silver data show some overlap, with generally lower values in native Cu, at levels from hundreds of ppb to tens of ppm. Platinum group elements (PGE) occur at ppb levels or below in all samples. Pt (up to ≈ 10 ppb in smelted Cu, ≤ 1 ppb in native Cu) may have some value as an extra discriminant.

Optical Properties and Textures:

Fresh surfaces of the metals can be reliably separated by colour into reddish copper ($>98\%$ Cu) and yellow, Zn-rich brass. In terms of copper samples, materials identified chemically as smelted metal all carry dispersed micron-scale blebs of cuprite (Cu oxide) slag, a feature completely absent from the native coppers. Textures of the smelted materials are reminiscent of sulphide fire assay beads and the intermediate products of modern copper refining.

Native Copper Mineralogy:

A literature survey suggests that the occurrence of native Cu with high levels of PGE is largely restricted to mafic-ultramafic rocks in ophiolite complexes, as in the Acoje (Zambales) ophiolite of the Philippines and the Blue Mountains of Jamaica. Enrichments of Pt and/or Pd to ppm or even percent levels may occur in micron-scale copper grains, probably during late post-magmatic events such as low-temperature serpentinization. Fine-grained copper in these and other ophiolites, and equally small-scale 'mineralogical' finds of native Cu in proximity to platinum group minerals are also reported from some mafic layered intrusions, such as the Duluth complex (Minnesota) and the Muskox intrusion (Northwest Territories). These sources of native Cu would be much too fine-grained to directly supply ancient metalsmiths. In Europe, many ores could enrich smelted copper in Au and Ag, but high PGE enrichment from comparatively refractory PGE ore types is less likely, and remains hypothetical.

This Earth Science study of archaeological provenance is underpinned by four complementary types of information, as noted in this abstract. These are: (a) the geology of native copper deposits and surrounding host rocks, (b) the nature of mineral assemblages containing native Cu, (c) the optical properties and textures of metal samples and (d) the chemistry of copper nuggets and artifacts. The presentation will include illustrations of the key factors, with diagnostic evidence such as photomicrographs and chondrite-normalised PGE patterns.

References:

- BEUKENS, R.P., PAVLISH, L.A., HANCOCK, R.G.V., FARQUHAR, R.M., WILSON, G.C., JULIG, P. and ROSS, W., 1992, Radiocarbon dating of copper archaeological artifacts. *Radiocarbon* 34, 890-897.
- BROWN, A.C., 1992, Sediment-hosted stratiform copper deposits. *Geoscience Canada* 19, 125-141.
- FRIEDMAN, A.M., CONWAY, M., KASTNER, M., MILSTED, J., METTA, D., FIELDS, P.R. and OLSEN, E., 1966, Copper artifacts: correlation with source types of copper ores. *Science* 152, 1504-1506.
- HANCOCK, R.G.V., PAVLISH, L.A., FARQUHAR, R.M., SALLOUM, R., FOX, W.A. and WILSON, G.C., 1991, Distinguishing European trade copper and northeastern North American native copper. *Archaeometry* 33, 69-86.
- MAUK, J.L., KELLY, W.C., VAN DER PLUIJM, B.A. and SEASOR, R.W., 1992, Relations between deformation and sediment-hosted copper mineralization: evidence from the White Pine part of the Midcontinent rift system. *Geology* 20, 427-430.
- NICHOLSON, S.W., CANNON, W.F. and SCHULZ, K.J., 1992, Metallogeny of the Midcontinent rift system of North America. In 'Precambrian Metallogeny Related to Plate Tectonics' (Gaal, G and Schulz, K.J. editors), *Precambrian Research* 58, 1-446, pp.355-386.
- RAPP, G., HENRICKSON, E. and ALLERT, J., 1990, Native copper sources of artifact copper in pre-Columbian North America. In 'Archaeological Geology of North America' (Lasca, N.P. and Donahue, J. editors), *GSA Centennial Spec. Vol. 4*, 479-498.
- SEASOR, R.W. and BROWN, A.C., 1989, Syngenetic and diagenetic concepts at the White Pine copper deposit, Michigan. In 'Sediment-Hosted Stratiform Copper Deposits' (Boyle, R.W., Brown, A.C., Jefferson, C.W., Jowett, E.C. and Kirkham, R.V. editors), *GAC Spec. Pap.* 36, 710pp., 257-267.
- WILSON, G.C., KILIUS, L.R. and RUCKLIDGE, J.C., 1991, In situ analysis of precious metals in polished mineral samples and sulphide "standards" by accelerator mass spectrometry at concentrations of parts-per-billion. *Geochimica et Cosmochimica Acta* 55, 2241-2251.

Early Proterozoic ages from Central Wisconsin.

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The Pre-Penokean stratigraphy of Wisconsin has been subdivided into several distinct events. In Central Wisconsin previous work has identified ages clustering around 2.8 to 3.0 Ga and a second grouping at 2.5 Ga. To date very old ages similar to those found in the Watersmeet north of the Niagara Fault have not been identified in outcrop. Evidence for igneous, sedimentary or metamorphic events in Central Wisconsin following the Archean and prior to the Penokean is still equivocal and far from resolved, and there are no previously published U/Pb zircon ages for this interval. Suggestion of crust formation in this time interval can be inferred from Nd model age studies that have consistently produced model ages ranging from 1.8 to 2.3 Ga, although this interpretation has always been discounted in favor of mixing between Archean and juvenile crust, which are known to exist in this area. Constraints on the Pre-Penokean stratigraphy will be necessary to resolve both the details of the Penokean Orogeny and of crustal evolution for this portion of the North American craton. Towards these goals, U/Pb zircon geochronology and common lead studies on gneisses collected near the town of Thorp, have revealed a new crust forming event in Central Wisconsin.

Sample TH1 is a banded gneiss of tonalitic composition. Leucocratic layers are diffuse and more coarsely crystalline than the melanocratic layers. In outcrop and in thin section there is good evidence for migmatization. A package of upper amphibolite grade lithologies can be traced to the south. Sample WO1 collected three miles away is a leucocratic unit, crosscutting a thick amphibolite package. It is considered correlative with the migmatization to the north. A large volume of TH2 was collected from freshly blasted material for mineral separates and whole rock analysis, and sampling was not able to resolve between leucocratic and melanocratic layers. Conventional U/Pb analyses on six zircon fractions produced an upper intercept age of 2264 ± 70 Ma (MSWD=47) and a lower intercept age of 528 ± 200 Ma. Zircon evaporation data give plateau ages ranging from 2056 ± 10 Ma ($T=1580^\circ\text{C}$, 48 ratios) to 2218 ± 3 Ma ($T=1640^\circ\text{C}$, 30 ratios). The lack of Archean or Penokean evaporation ages is strong evidence against interpreting TH2 as a mixing age. Additional age constraints are provided by common lead leach data on feldspars. TH2 has an isochron age of 2018 ± 710 Ma on 4 leach steps (MSWD=11.3) and WO1 has a age of 2050 ± 170 on 4 leach steps (MSWD=2.8). In addition WO1 has a Stacey-Kramer model age intercept of 2149 Ma.

Interpreted together, these data provide compelling evidence for a new gneiss formation event in Central Wisconsin during the Early Proterozoic. It is not known how widespread this event is throughout the area, or whether is restricted to a distinct block. The presence of crust formation ages during this time interval also requires reevaluation of Nd model age studies and the possibility exists that later Penokean and Wolf River magmatism has interacted not with minor amounts of Archean crust but with more voluminous amounts of younger crust. On a broader scale the difference between these two interpretations centers around whether an episodic or a steady crustal growth rate is more appropriate for this portion of the craton. The recognition of crystallization ages during the Early Proterozoic interval certainly suggest that more consideration should be given to the later model.

Lithotectonic and Structural Setting of Mineralization in the Manitouwadge Greenstone Belt, Northwestern Ontario.

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The Cu-Zn deposits of the Manitouwadge greenstone belt lie within an upper amphibolite-facies, highly deformed remnant of supracrustal rocks in the Wawa subprovince near Quetico subprovince boundary (Fig. 1). Our objective is to gain an understanding of mineralization and alteration in the Manitouwadge belt, with respect to their origin, setting and subsequent modifications during a complex deformational and metamorphic history. The results presented here are based on one and a half field seasons of detailed mapping (1:5000) and preliminary petrography and structural analysis.

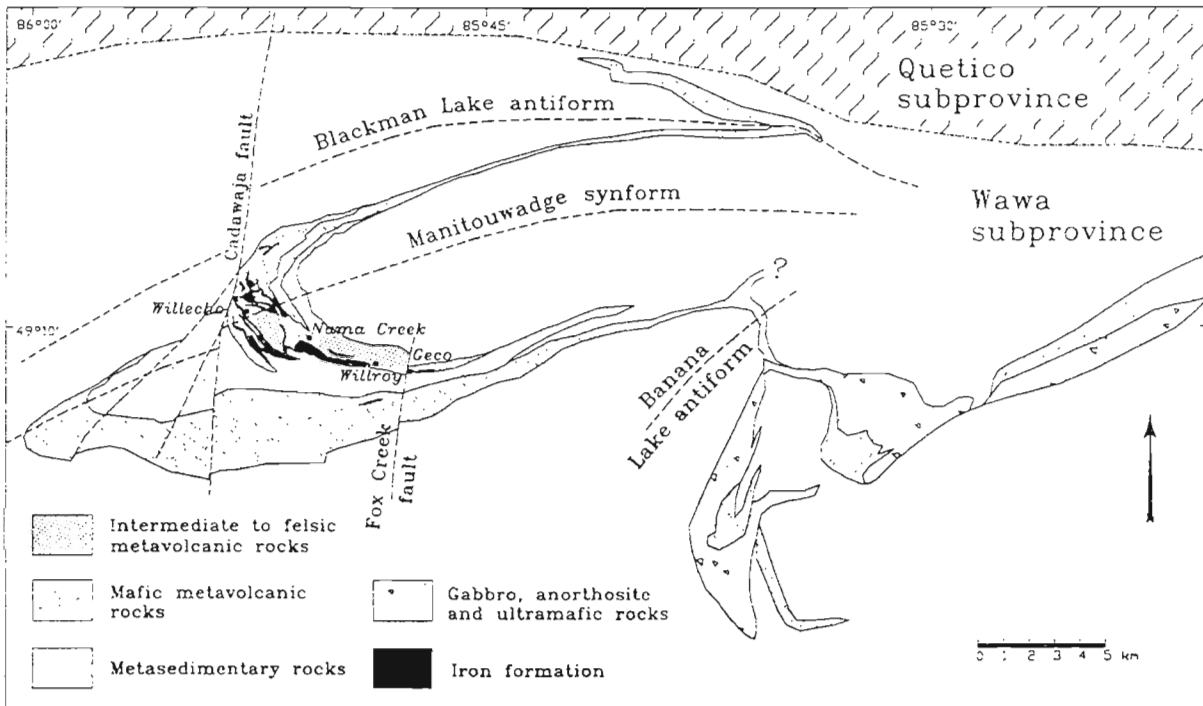


Figure 1. Regional geology adapted from Williams and Breaks (1990a).

Supracrustal rocks in the Manitouwadge belt include mafic and felsic volcanic and volcanoclastic rocks, a variety of altered rocks and iron formation, all characterized by metamorphic mineral assemblages. Mineralization is associated with iron formation and altered rocks. There are two mappable alteration units: 1) orthoamphibole-garnet-cordierite gneiss — interpreted as representing a zone of alkali depletion and Fe-Mg enrichment developed in the stratigraphic footwall to mineral deposits (Freisen et al., 1982), and 2) muscovite-sillimanite or sillimanite-garnet-biotite±cordierite schists — previously interpreted as fault zones (Milne, 1974) and as altered volcanogenic rocks (Freisen et al., 1982). In addition, extensive occurrences of hornblende-garnet±epidote±diopside assemblages in felsic volcanic rocks and breccias, especially near contacts with iron formation, constitute a third type of alteration. This calc-silicate alteration type may have had a prolonged history, extending from synvolcanic to post-peak metamorphic (Pan and Fleet, 1992).

A crude symmetry of rock units across the Manitouwadge belt led Touborg (1973) and Robinson (1979) to propose that the supracrustal rocks were repeated in a nappe structure, subsequently refolded to its present synformal shape. Southerly younging interpreted from metal and alteration zoning in the Wilroy and Geco areas (Suffel et al., 1971; Freisen et al., 1982), and northerly younging primary structures in the south of the belt (W. Bates, pers. comm.; Williams and Breaks, 1990b), support the proposed syncline. Our observations of the association of map-scale truncations with straight gneisses (annealed early mylonitic rocks) suggest that repetition of units, including some mineralized rocks, within the belt may be due to early ductile thrusting (D1) (Fig. 2). Subsequent deformation (D2), during peak metamorphism, produced map-scale asymmetric counterclockwise (west-directed) folds, strong northeasterly-plunging mineral lineations and the dominant foliation. Later dextral motion (D3-D4) produced the

regional z-shaped asymmetry of the belt (Fig. 1), the Manitouwadge synform, reorientation of the dominant foliations and lineations, and local kink folds and crenulation cleavage.

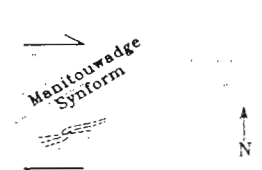
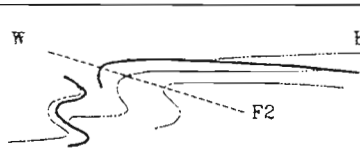
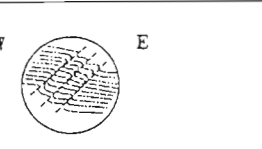
STRUCTURAL HISTORY						
	Tectonic/Structural Interpretation				Tectonic/Structural Interpretation	
D1	Low angle folding and thrusting			D3	Shortening to produce steep dips ? Regional east-directed (dextral) folding/shearing	
D2	West-directed folding			D4	Continued dextral shear	

Figure 2. Summarized structural history.

- Friesen, R.G., Pierce, G.A., and Weeks, R.M., 1982, Geology of the Geco base metal deposit: Geological Association of Canada, Special Paper 25, p. 343-363.
- Milne, V.G., 1974, Map 2280, Mapledoram-Gemmell, Thunder Bay District, scale 1:12,000, Ontario Division of Mines.
- Pan, Y., and Fleet, M.E., 1992, Mineralogy and genesis of calc-silicates associated with Archean volcanogenic massive sulphide deposits at the Manitouwadge mining camp, Ontario: Canadian Journal of Earth Sciences 29, p. 1375-1388.
- Robinson, P.C., 1979, Geology and evolution of the Manitouwadge migmatite belt, Ontario, Canada: Ph.D. Thesis, University of Western Ontario, 367 pages.
- Suffel, G.C., Hutchinson, R.W., and Ridler, R.H., 1971, Metamorphism of massive sulfides at Manitouwadge, Ontario, Canada: Society of Mining Geologists of Japan, Special Issue 3, p. 235-240.
- Touborg, J.F., 1973, Structural and stratigraphical analysis of the Geco sulphide deposit in Manitouwadge, northwestern Ontario: [abs] 19th Annual Institute on Lake Superior Geology, p. 38-39.
- Williams, H.R. and Breaks, F.W., 1990a, Geology of the Manitouwadge-Hornepayne area: Ontario Geological Survey, Open File Map 142, scale 1:50,000.
- Williams, H.R. and Breaks, F.W., 1990b, Geological Studies in the Manitouwadge-Hornepayne area: Ontario Geological Survey, Miscellaneous Paper 151, p. 41-47.
- Zaleski, E. and Peterson, V.L., 1993, Lithotectonic setting of mineralization in the Manitouwadge greenstone belt, Ontario: preliminary results: Current Research, Part C, Geological Survey of Canada, Paper 93-1C, p. 307-317.

A CONTINENTAL CRUST FRACTURE INITIATION PATTERN AND HYPOTHETICAL MECHANISM

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A cursory observation of the North American Midcontinent Precambrian Rift as detailed on a Bouguer gravity map filtered to exclude features with wavelengths greater than 250 km, reveals a peculiar symmetry between southern Minnesota and eastern Nebraska. The symmetry expressed is reflected relative to both a primary axis oriented from the NW to the SE, and a secondary axis 90 degrees to the first, oriented from the NE to the SW. The primary and secondary axes of symmetry of the figure on the map's surface, in reality, 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, simple natural symmetry is the physical manifestation of a spatial pattern that reflects an invariance of distance dependent causal relationship.

It will be hypothesized that the crust fracture geometry is the resultant product of three principal and probably related modes of influence. The first is an impulse shock from within the primary radial plane and probably originating near or within the crust. The second being a crustal tension orientation resulting from a radial plane, which submits the underside of the crust to diverted and opposing resistive flow forces. The third mode is a functionally continuous distribution of forces applied to the underside of the crust along the secondary axis by the diversionary shear stresses from within the same plume's up welling flow head. The symmetrical geometric curvature produced by the propagation of crustal fracture under these conditions, as displayed here most vividly, has much the same profile as an archer's recurve bow.

It is further proposed that the entire rift fracture started with this figure, and that the figure will be shown to be a signature profile with many past recorded occurrences world wide. The smooth and uniform curvature results because the fracture development within this pattern is relatively rapid with a tremendous initial release of convection-related stresses, which does not allow for much localized structural dislocation of crustal constituents to be a factor in the propagation directions.

A speculative morphological development of the triple junction of fracture is offered to supplant its previously imagined role with the rift's origin and development. The signature bow fracture hypothesis is further supported by evidence of the regular appearance of five collateral indicating features which are logically related to the bow's development and are noted at several other suspected bow fracture locations. Thus, primarily from a mechanistic understanding of simple natural symmetry, the creative application of pattern recognition, and considerations of geometric material stress projection, a hypothetical developmental scenario is presented.

It is further conjectured that 1.2 b.y. ago, when the rift initially developed, the region of continental crust where it now exists was positioned over a roughly linear upper mantle convection plume, which originally established and may continue to define today's northern margin of the Caribbean plate.

This seems evident because upon careful inspection of a colored composite magnetic anomaly map of the eastern United States, a large semicircular pattern of magnetic lows will emerge from the clutter of background details. It soon becomes apparent that an ancient semicircular surface rift passing through Wisconsin, lower Michigan and Ohio, is clearly delineated by the magnetic insulating properties of its sedimentary fill. It measures about 900 km in diameter, and its arc center is located in central Indiana. On its eastern end, a linear extension to the rift is clearly visible running nearly parallel to the western Appalachian basin and extending southward through to Alabama. On its western end, a similar, nearly parallel extension can faintly be seen running all the way through to eastern

Kansas. The distance across these linear margins measures between about 900 to 1040 km, it is only slightly larger than the semicircular arc diameter. This sedimentary filled surface pattern, in its totality, physically corresponds rather closely to the present day peripheral margin of the eastern end of the Caribbean plate.

The interesting disparity is that this rift system, so closely matched to the Caribbean plate's eastern profile, does not pass over the signature bow in central Iowa. For the same convection cell to have initiated the Midcontinent Rift, the continent would have to be translated 162 km and rotated about 2.5 degrees. The Iowa fracture would then line up correctly with the western convection margin, but the eastern convection margin would pass through southwest Ohio and central Kentucky. Surprisingly, this ancient surface rift filled with sedimentary deposit, and was shown to have possibly developed simultaneously with the Iowa fracture. Additionally, the paleogeographic position of the secondary axis of the Iowa bow fracture, very closely matches the present day position of the Caribbean plate's northern margin.

These coincidences seem to imply that two circumstantial dwellings of the North American continent above the same convection cell that defined today's oceanic plate, resulted in the near creation of related plate profiles at these continental locations. Could an upper mantle convection cell positioned under the present day Caribbean ocean, have created these continental and oceanic crustal pattern delineations? It is suggested that as a composition implies a history, the coincidence of three indicated physical matchings of derivative effects in accessible proximity, begs for thoughtful consideration of a common causal source.

MANGANESE-RICH ONCOLITES IN THE BIWABIK IRON FORMATION, THUNDERBIRD MINE,
MESABI IRON RANGE, MINNESOTA

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The Upper Cherty Member of the Biwabik Iron Formation contains an algal unit consisting generally of finger-sized algal stromatolites. However, at the Thunderbird North Mine near Eveleth the 0.5 to 1.5 m thick algal unit consists of rhodochrosite-rich algal pisolites (oncolites). Oncolites range in size from less than 1 mm to more than 6 cm in major axis, and vary in shape from spheroidal and pear-shaped to ellipsoidal or disk-shaped, usually reflecting the shape of the nucleus. The majority of oncolites over 2 mm in diameter are ellipsoidal. The oncolites are composed of concentric laminae ranging in thickness from 0.01 mm to 0.1 mm around nuclei of chert, jasper, pisolites, and detached layers of algal stromatolite. Some oncolites are asymmetric with thicker laminations on one side. Many oncolites which exhibit this asymmetric characteristic have finger algae-type growth on the thicker side. Some oncolites show erosionally truncated laminae overlain by complete laminae. In places, smaller oncolites are incorporated within the laminae of larger oncolites. Green, opaline chert occurs at the base of the unit, grading upward into red opaline chert. The zone containing the red and green chert has been extensively reworked. Syneresis cracks are prominent, and fragments of red chert serve as nuclei for many oncolites.

Three distinct mineral assemblages comprise the algal unit as determined by X-ray diffraction (XRD), energy dispersive X-ray analysis (EDAX), and optical microscopy. The first assemblage consists mainly of rhodochrosite with siderite, magnetite, hematite, calcite, and organic material; the second of siderite, chert, hematite, and magnetite; and the third mostly of red chert (jasper) with hematite. Contacts are gradational between the first and second assemblages, but the third assemblage, which comprises approximately 80% of the algal unit, cuts sharply across the first and second assemblages. Contacts between assemblages are oblivious to sedimentary structures, and a single algal pisolite may contain more than one mineral assemblage.

Oncolites found in the Thunderbird North Mine have an origin similar to algal stromatolites found elsewhere in the Biwabik and Gunflint Iron Formations, but most likely formed in a high energy environment such as a tidal channel where strong surges prevented the algal growths from becoming attached to the substrate. The most plausible explanation for the high concentration of manganese in the original minerals is attributable to biogenic processes of the algae and bacteria that formed the oncolites. Changes in the chemical environment after deposition resulted in replacement of manganese and iron carbonates by chert and oxidation of ferrous iron to hematite.