

# **INSTITUTE ON LAKE SUPERIOR GEOLOGY**

## **PROCEEDINGS**

**36th Annual Meeting**

**May 9-12, 1990**

**held at**

**Thunder Bay, Ontario**

## **H. L. JAMES VOLUME**



**VOLUME 36**

**May 1990**

**Part 1. Abstracts**

**Organizing Committee, 36th Annual Meeting, ILSG (1990)**

**The Organizing Committee comprises the following members of the**

**Department of Geology  
Lakehead University  
Thunder Bay, Ontario P7B 5E1**

**General Chairman: Manfred M. Kehlenbeck**

**Program Chair and Abstract Editor: Philip W. Fralick**

**Field Trip Guidebook Editor: Graham J. Borradaile**

**Volume 36 consists of**

**Part 1: Abstracts**

**Part 2: Field Trip Guidebook**

**Reference to material in Proceedings Volume should follow the example below:**

**Brown, Bruce A., 1989, Significance of Conglomerates in the Baraboo quartzite of southeastern Wisconsin [abst.]; Institute on Lake Superior Geology Proceedings, 35th Annual Meeting, Duluth, MN, 1989; Houghton, MI, v. 35, part 1, p. 11-12.**

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### Dedication

*The pioneer research by Harold L. James formed the widely accepted foundation which stimulated the work of many geologists. His contributions and ideas have become so intricately interwoven in many of the later studies that their significance and individuality are often obscured.*

*Born a Canadian in 1912, Hal graduated from the State College of Washington in 1938. During World War II he mapped chromite, manganese, asbestos, talc and zinc in Montana for the U.S. Geological Survey, and after receiving his PhD from Princeton University in 1945 continued with the U.S. Geological Survey with brief interruptions at Northwestern University and the University of Minnesota. After the War his research interests focused on the iron-formations in the Lake Superior region. His appointment as Chief Geologist culminated his 50-year long career with the Survey. He is now retired and lives in Bellingham, Washington. After retirement from the Survey, he served as chairman of the IGUS Subcommittee on Precambrian Stratigraphy. The concepts and time lines associated with WXYZ Precambrian terminology which he put forward for consideration are still actively used to define Precambrian time and stratigraphy.*

*His principal work for many years involved meticulous mapping and microscopic study of iron deposits in Michigan. His keen eye pulled from the rock conclusions that today provide provocative insight into the geological evolution of this region. His recognition of differences in the mineralogy of iron-formations due to original sedimentation as opposed to difference in response to later metamorphism led to the recognition of different depositional basins for the various ore types and regional metamorphic zoning patterns. The facies originally defined from iron-formation studies now are major tools in unravelling Early Proterozoic terrane. The recognition of regional zonal metamorphic patterns led to concepts of older Archean remobilized basement and stable Proterozoic cratons that characterize working models for early Proterozoic continental margins.*

*He was extremely active in the Society of Economic Geologists, serving as President in 1970. He was awarded the Penrose Medal from the Society in 1976 in recognition of his comprehensive study of Precambrian rock of the Lake Superior region and for establishing the origin and history of iron deposits associated with them.*

*It is with great pleasure that the Institute on Lake Superior Geology recognizes Harold L. James' life-time contribution by dedicating this volume to him.*

*M. G. Mudrey, Jr.*

**36th ANNUAL**  
**INSTITUTE ON LAKE SUPERIOR GEOLOGY**

**Proceedings and Abstracts**

**Thunder Bay, Ontario**

**May 10 and 11, 1990**

*Organized by*

*M. M. Kehlenbeck, Lakehead University, Thunder Bay*  
*G. J. Borradaile, Lakehead University, Thunder Bay*  
*P. W. Fralick, Lakehead University, Thunder Bay*

VOLUME 36.

PART 1 PROGRAM AND ABSTRACTS

PART 2 FIELD TRIP GUIDEBOOK

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## INSTITUTES ON LAKE SUPERIOR GEOLOGY

| <u>INSTITUTE NUMBER</u> | <u>DATE</u> | <u>PLACE</u>                    |
|-------------------------|-------------|---------------------------------|
| 1                       | 1955        | Minneapolis, MN                 |
| 2                       | 1956        | Houghton, MI                    |
| 3                       | 1957        | East Lansing, MI                |
| 4                       | 1958        | Duluth, MN                      |
| 5                       | 1959        | Minneapolis, MN                 |
| 6                       | 1960        | Madison, WI                     |
| 7                       | 1961        | Port Arthur, Ont. (Thunder Bay) |
| 8                       | 1962        | Houghton, MI                    |
| 9                       | 1963        | Duluth, MN                      |
| 10                      | 1964        | Ishpeming, MI                   |
| 11                      | 1965        | St. Paul, MN                    |
| 12                      | 1966        | Sault Ste. Marie, WI            |
| 13                      | 1967        | East Lansing, MI                |
| 14                      | 1968        | Superior, WI                    |
| 15                      | 1969        | Oshkosh, WI                     |
| 16                      | 1970        | Thunder Bay, Ont.               |
| 17                      | 1971        | Duluth, MN                      |
| 18                      | 1972        | Houghton, MI                    |
| 19                      | 1973        | Madison, WI                     |
| 20                      | 1974        | Sault Ste. Marie, Ont.          |
| 21                      | 1975        | Marquette, MI                   |
| 22                      | 1976        | St. Paul, MN                    |
| 23                      | 1977        | Thunder Bay, Ont.               |
| 24                      | 1978        | Milwaukee, WI                   |
| 25                      | 1979        | Duluth, MN                      |
| 26                      | 1980        | Eau Claire, WI                  |
| 27                      | 1981        | East Lansing, MI                |
| 28                      | 1982        | International Falls, MN         |
| 29                      | 1983        | Houghton, MI                    |
| 30                      | 1984        | Wausau, WI                      |
| 31                      | 1985        | Kenora, Ont.                    |
| 32                      | 1986        | Wisconsin Rapids, WI            |
| 33                      | 1987        | Wawa, Ont.                      |
| 34                      | 1988        | Marquette, MI                   |
| 35                      | 1989        | Duluth, MN                      |
| 36                      | 1990        | Thunder Bay, Ont.               |

## CONSTITUTION OF INSTITUTE ON LAKE SUPERIOR GEOLOGY

### Article I

#### Name

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

### Article II

#### Objectives

The objectives of this organization are:

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

### Article III

#### Status

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

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

Minn. Stat. Anno. 290.01, subd. 4

Minn. Stat. Anno. 290.05(9)

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

### Article IV

#### Membership

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

### Article V

#### Meetings

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

### Article VI

#### Directors

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

### Article VII

#### Officers

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

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

### Article VIII

#### Amendments

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

## BY-LAWS

### I. Duties of the Officers and Directors

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

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

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

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

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

### II. Duties and Expenses

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

### III. Rules of Order

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

### IV. Amendments

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

Award Guidelines  
SAM GOLDICH MEDAL

Preamble

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

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

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

Award Guidelines

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

April 4, 1981

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

### **STUDENT TRAVEL AWARD**

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

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

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

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

### **BOARD OF DIRECTORS**

- 1990 M. M. Kehlenbeck  
Department of Geology, Lakehead University, Thunder Bay, Ontario P7B 5E1
- 1989 R. W. Ojakangas (with J. C. Green and T. B. Holst)  
Department of Geology, University of Minnesota, Duluth, Duluth, Minnesota 55812
- 1988 J.S. Klasner (with J. D. Hughes and K. J. Schulz)  
Department of Geology, Western Illinois University, Macomb, Illinois 61455
- 1987 R. P. Sage (with E. D. Frey)  
Ontario Geological Survey, Ministry of Northern Development and Mines,  
77 Grenville Street, Toronto, Ontario M7A 1W4
- Secretary-Treasurer  
J. Kalliokoski  
Department of Geology and Geological Engineering, Michigan Technological  
University, Houghton, Michigan 49931

### **LOCAL COMMITTEE**

- |                  |                             |
|------------------|-----------------------------|
| M. M. Kehlenbeck | General Chairman            |
| P. W. Fralick    | Program and Abstract Editor |
| G. J. Borradaile | Field Trip Guidebook Editor |

### **STUDENT PAPER AWARD COMMITTEE 1990**

- |                         |                                               |
|-------------------------|-----------------------------------------------|
| J. S. Klasner, Chairman | Western Illinois University, Macomb, Illinois |
| W. Kangas               | Cleveland Cliffs Iron Co., Ishpeming, MI      |
| D. Southwick            | Minnesota Geological Survey, St. Paul, MN     |

### **GOLDICH MEDAL COMMITTEE 1989-90**

- |                         |                                                                              |
|-------------------------|------------------------------------------------------------------------------|
| J. J. Brummer, Chairman | Brummer Consulting, Toronto, Ontario                                         |
| M. G. Mudrey, Jr.       | Wisconsin Geologic and Natural History Survey, Madison, WI                   |
| F. W. Cambray           | Dept. of Geological Sciences, Michigan State University,<br>East Lansing, MI |

### **GOLDICH MEDAL RECIPIENT 1990**

*Dr. Ken D. Card*, Lithosphere and Canadian Shield Division, Geological Survey of Canada,  
588 Booth Street, Ottawa, Ontario K1A 0E4.

Medal awarded by M. M. Kehlenbeck, Lakehead University, Thunder Bay, Ontario.

### **BANQUET SPEAKER**

At press time we are unable to confirm our banquet speaker due to circumstances beyond our control.

### **ACKNOWLEDGMENTS**

We three (M. M. Kehlenbeck, G. J. Borradaile, and P. W. Fralick) gratefully recognize the unselfish contributions of time and energy, by many individuals, without which this meeting could not have taken place.

We especially thank our Department Secretary, Sandra Millar, for her secretarial skills and efficiency in compiling the mailing lists, brochures, Institute volumes, and attending to many other tasks.

The drafting of illustrations for the Guidebook, as well as assistance during the technical sessions and field trips, was ably provided by Sam Spivak and Reino Viitala. Two of our graduate students, Barbara Seemayer and Dave Nicol, handled the mailing of brochures, helped on the field trips and did many other jobs. The assistance of Bob Cornell and Jim Podd of Lakehead University, David Thomson (Airlane Hotel) and numerous company personnel is appreciated.

Thanks for a job well done also go to:

- Joe Brummer, Mike Mudrey and Bill Cambray (Goldich Medal Committee)
- Richard Sutcliffe, Steve Kissin, Maurice Lavigne and John Scott (Field Trip leaders)
- John Klasner, Dave Southwick and Bill Kangas (Student Paper Award Committee)
- To all those brave souls who conduct the technical sessions and keep the program on time.

Special thanks to Joe Kalliokoski for his support and sage advice during critical moments in the planning process.

Since no list of this type is ever complete, we thank everyone else who contributed.

## 35th ANNUAL INSTITUTE ON LAKE SUPERIOR GEOLOGY

Duluth, Minnesota 1989

The 35th annual meeting of the Institute on Lake Superior Geology was held from May 3-6, 1989, in Duluth, Minnesota. The meeting was hosted by the University of Minnesota, Duluth. Richard W. Ojakangas served as General Chairman, John C. Green served as Program Chairman and Abstract Editor, and Timothy B. Holst served as Field Trip Chairman and Guidebook Editor. Several other UMD faculty members and graduate students assisted in various ways. Technical sessions and the banquet were held at the Radisson Hotel on Thursday and Friday, May 4 & 5. A total of 202 persons registered for the meeting. Thirty papers were presented orally and 24 were presented as posters. Two field trips were held on Wednesday May 3 and two were held on Saturday May 6.

Paper sessions were organized into four one-half day sessions, as follows: "Midcontinent Rift"; "Mostly Economic and Quaternary," "Mostly Proterozoic" and "Mostly Archean".

A total of 124 persons registered for field trips. Field trip 1, led by John C. Green, was to the North Shore Rhyolites of Minnesota (30 persons). Field trip 2, led by Timothy B. Holst was a visit to Penokean Structural Terranes of East-Central Minnesota (24 persons). Field trip 3, led by Karl Seifert, James Olmstead, and Ken Klewin was to the Mellon Complex, Wisconsin (23 persons). Field trip 4, entitled Archean Gold Occurrences and their Structural Settings, Minnesota, had eight leaders, as follows: J. Welsh, D. England, D. Groves, E. Levy, P. Hudleston, D. Southwick, R. Bauer, W. Ulland (47 persons).

A total of 159 people attended the annual ILSG banquet. Mike Mudrey, Jr. presented the Goldich Medal to J. Kalliokoski of Michigan Technological University for his many contributions to teaching and research on the Lake Superior region, as well as for his long service to the Institute. The banquet speaker was Frederick J. "Sam" Sawkins of the University of Minnesota, Twin Cities, who spoke on "Ore genesis models for volcano-plutonic arc system: An agnostic view of the conventional wisdom." His agnostic views stimulated discussions for the remainder of the meeting.

In continued support of student participation in the meeting, the ILSG assisted seven students with small transportation stipends and waiver of registration fees. Six UMD students were given waivers of registration and banquet fees for their valued assistance before and during the meeting and field trips. An award of \$150 was presented to Tom Suszek of the University of Minnesota, Duluth, for the best oral student presentation, and a \$150 award was presented to Daniel Holm of Harvard University for the best poster paper. John Klasner, Ray Anderson, and Keith Laskowski served on the Best Student Paper Committee.

An ILSG Board of Directors Luncheon Meeting was held on May 4. It was attended by B. Brown, J. C. Green, J. Greenburg, T. Holst, J. Hughes, J. Kalliokosi, M. Kehlenbeck, J. Klasner, R. Ojakangas, R. Sage, S. Sawkins, and K. Schulz. The following items were discussed:

(1) \$500 from the ILSG Treasury in the U.S. and \$500 from the ILSG treasury in Canada will be made available for travel support for students presenting papers.

(2) John Hughes read a letter from Burt Boyum regarding the making of a video on the Mining History of the Marquette Range. (This was the title of a field trip at the 34th ILSG at Marquette in 1988). ILSG will support the idea and urges that acknowledgment of Burt Boyum and Bob Reed be included in the video.

(3) Voted to ask Bill Cambray to serve on the Goldich Medal Committee, replacing R. W. Ojakangas whose term has expired.

(4) The Treasurer's report by J. Kalliokoski was received. The balance in the General account as of April 30, 1989 was \$5,593.03. The Goldich Medal Fund contained \$352.15. M. Kehlenbeck, Treasurer of the Canadian account, reported a balance of \$10,299.90 as of April 30, 1989.

We wish to thank all those who helped to make this a successful ILSG meeting, including all the speakers, the poster-presenters, the field trip leaders, the session chairs, the Student Paper Judges, the Goldich Medal Committee, the Banquet Speaker, Mary Nash (UMD Geology Department Executive Secretary) who handled the finances, Joan Hendershot (UMD Geology Department Senior Secretary) who did nmuch of necessary arrangements, numerous student assistants, the guiding Board of Directors, and J. Kalliokoski, the Secretary-Treasurer of ILSG. Finally, the advice and sympathy of the organizers of previous meetings has been most helpful.

Respectfully submitted,

R. W. Ojakangas

J. C. Green

T. B. Holst

## CALENDAR OF EVENTS AND PROGRAM

### WEDNESDAY, MAY 9

#### Field Trips 1, 2, and 4

*Field trips depart at 8 a.m. from the rear parking lot of the Airline Motor Hotel. Lunch is provided.*

TRIP NO. 1\* R. Sutcliffe (leader) - Mafic intrusions, PGE mineralization and granitoid rocks of the Lac des Illes area.

VANS

TRIP NO. 2\* G. Borradaile (leader) - Geology of the Shebandowan and Quetico Archean Subprovinces.

VANS

#### FOR PEOPLE WHO ARE GOING ON A POST-MEETING TRIP

TRIP NO. 4\* M. Lavigne and J. Scott (leaders) - Base metal mineralization in the Shebandowan Greenstone Belt.

BUS

#### FOR PEOPLE WHO ARE ALSO GOING ON TRIP 1

*All trips terminate at the Airline Motor Hotel.*

4 p.m. - 8 p.m. Registration and Check-in for Pre-registrants

7 p.m. - 10 p.m. Welcome Get-together and Poster Displays  
Cash Bar

\* These field trips have been duplicated (i.e. pre-meeting and post-meeting).

**THURSDAY, MAY 10**

**TECHNICAL PROGRAM**

**MORNING SESSION**

**CHAIRS: Val W. Chandler and Donald M. Davidson, Jr.**

7:55 WELCOME

- |    |      |                                                                |                                                                                                                                                       |
|----|------|----------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1. | 8:00 | Jablinski, J.D.*<br>Holst, T.B.<br>Cuthill, J.<br>Oliver, D.C. | Structural analysis of Archean metasedimentary rocks in the vicinity of the Mineral Hill Gold mine, Jardine, Montana.                                 |
| 2. | 8:20 | Pankka, H.S.*<br>Bornhorst, T.J.                               | Finnish Proterozoic gold occurrences and implications for the Lake Superior Region.                                                                   |
| 3. | 8:40 | Hayes, M.J.*<br>Nelson, C.L.                                   | Geology of Wright County using well log data.                                                                                                         |
| 4. | 9:00 | Venzke, E.A.*                                                  | The geology of the Greenwood Lake area Duluth Complex, Lake County, Northwestern Minnesota.                                                           |
| 5. | 9:20 | Weiblen, P.<br>Sabelin, T.<br>Saini-Eidukat, B.<br>Iwasaki, I. | The role of volatiles in the formation of the Platinum Group Element deposits in the Middle Proterozoic and the Triassic Noril'sk-Talnakh Intrusions. |

9:40 COFFEE BREAK and POSTER SESSION

**CHAIRS: Ted J. Bornhorst and John Green**

- |    |       |                                                       |                                                                            |
|----|-------|-------------------------------------------------------|----------------------------------------------------------------------------|
| 6. | 10:00 | Ojakangas, R.W.<br>Marmo, J.S.<br>Heiskanen, K.I.     | Lower Proterozoic glaciogenic deposits: A North America-Baltic Connection? |
| 7. | 10:20 | Wilkin, R.T.*<br>Mavrogenes, J.A.*<br>Bornhorst, T.J. | Archean granitoids of northern Marquette County, Michigan.                 |

8. 10:40 Juneau, P.J. Origin and petrology of iron silicate-rich bodies in the Biwabik iron formation, Minnesota.
9. 11:00 Jerde, E.A.\* Reverse zonation in the Lester River Sill, Duluth, Minnesota, and evidence for polybaric fractionation.
10. 11:20 Aubut, A. Geology of the Shebandowan Mine.

11:40 LUNCH BREAK

*Tour of Rock Mechanics Lab., Lakehead University  
Sign-up at Registration Desk*

1:00 POSTER SESSION WITH AUTHORS PRESENT

### AFTERNOON SESSION

CHAIRS: Ed Frey and Tim Holst

11. 1:30 Kean, W.F.  
Schneiker, R. Paleomagnetism of Baraboo interval rocks in Wisconsin.
12. 1:50 Chandler, V.W.  
Morey, G.B. The paleomagnetism of the early Proterozoic Sioux quartzite.
13. 2:10 Bodus, T.M.\*  
Kean, W.F. Magnetic survey of the Niagara fault system in northeastern Wisconsin and northwestern Upper Peninsula Michigan.
14. 2:30 Lagowski, J.\*  
Johnson, A.  
Gere, M. Geology and economic potential of northern Michigan graphite.
15. 2:50 Cannon, W.F.  
Peterman, Z.E.  
Sims, P.K. Structural and isotopic evidence for middle Proterozoic thrust faulting of Archean and early Proterozoic rocks near the Gogebic Range, Michigan and Wisconsin.

3:10 COFFEE BREAK and POSTER SESSION

**CHAIRS: Peter Hudleston and John Klasner**

- |     |      |                             |                                                                                                                    |
|-----|------|-----------------------------|--------------------------------------------------------------------------------------------------------------------|
| 16. | 3:30 | Read, W.F.*                 | New evidence that Limestone Mt., Michigan is part of a large impact structure.                                     |
| 17. | 3:50 | Saini-Eidukat, B.*          | Review of analytical methods for the determination of platinum group elements.                                     |
| 18. | 4:10 | Victory, D.*<br>Watkins, I. | The mineral relief of surfaces produced by sanding with quartz percussion, thermal disaggregation, and weathering. |

***Tour of Rock Mechanics Lab., Lakehead University  
Sign-up at Registration Desk***

6:30 CASH BAR

7:30 BANQUET

- ⌘ Presentation of the Goldich Medal to K.D. Card, Geological Survey of Canada, by M. M. Kehlenbeck.
- ⌘ Dedication of I.L.S.G. volume 36 to H. L. James, by M. G. Mudrey, Jr.
- ⌘ Speaker: The Organizing Committee will do everything possible to provide suitable entertainment. We are presently unable to confirm our speaker.

**FRIDAY, MAY 11**

**TECHNICAL PROGRAM**

**MORNING SESSION**

**CHAIRS: Gene LaBerge and Michael G. Mudrey, Jr.**

- |     |      |                                                       |                                                                                                                                  |
|-----|------|-------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------|
| 19. | 8:00 | Matty, D.J.<br>Stahl, S.D.<br>Heft, A.<br>Huysken, K. | Petrologic and geochemical evolution of the Penokean Peavy Pond Complex, Iron County, Michigan.                                  |
| 20. | 8:20 | Miller, J.D.<br>Schaap, B.D.<br>Chandler, V.W.        | The Sonju Lake Intrusion and associated Keweenawan rocks: Geochemical and geophysical evidence of petrogenetic relationships.    |
| 21. | 8:40 | Green, J.                                             | Tridymite, other SiO <sub>2</sub> minerals and the P-T trajectory of Keweenawan lavas, Minnesota.                                |
| 22. | 9:00 | Paces, J.B.<br>Taylor, L.A.                           | Petrography, mineral chemistry, and geothermobarometry of mafic granulite and eclogite nodules from upper Michigan Kimberlites.  |
| 23. | 9:20 | Koehler, S.R.*                                        | Geological setting and geochemistry of the Bush Lake granite in relation to rare-element pegmatites, Florence County, Wisconsin. |

9:40 COFFEE BREAK and POSTER SESSION

**CHAIRS: Zell Peterman and Howard Poulsen**

- |     |       |                                                  |                                                                                                                         |
|-----|-------|--------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------|
| 24. | 10:00 | Kalliokoski, J.                                  | Geology of Presque Isle Point, Marquette, Michigan: A second look.                                                      |
| 25. | 10:20 | Jirsa, M.A.<br>Southwick, D.L.<br>Boerboom, T.J. | The significance of regional-scale left-lateral faulting in development of the Vermillion Greenstone Belt in Minnesota. |
| 26. | 10:40 | Nachatilo, S.A.*<br>Bauer, R.L.                  | Constraints on Archean versus Proterozoic deformation in Archean rocks of the Negaunee Area, Upper Michigan.            |

27. 11:00 Borradaile, G. Particulate flow and the deformation of rock: Field and experimental results.
28. 11:20 Gregg, W.J. Transposition structures in deformed rock, with examples from the Appalachians and upper Michigan.

11:40 LUNCH BREAK

*Tour of Rock Mechanics Lab., Lakehead University  
Sign-up at Registration Desk*

1:00 POSTER SESSION WITH AUTHORS PRESENT

### AFTERNOON SESSION

CHAIRS: William Cannon and David Southwick

29. 1:30 Mudrey, M.G. Tectonic ramifications of GNI/Argonne Lake Superior  
Dickas, A.B. Seismic data.  
McGinnis, L.D.  
Cannon, W.F.
30. 1:50 Roscoe, S.M. The reappearance of the Huronian in Wyoming.
31. 2:10 Davis, D.W. The Seine-Coutchiching problem reconsidered: U-Pb geochronological data concerning the source and timing of Archean sedimentation in the western Superior Province.
32. 2:30 Sims, P.K. The Great Lakes Tectonic Zone - a major north-verging late Archean collision zone.
- 2:50 PRESENTATION OF STUDENT PAPER AWARDS
- 3:00 COFFEE BREAK TAKE-DOWN POSTER PAPERS
33. 3:30 Watkins, I. Faults associated with the Penokean accretion of  
Shurr, G.W. allochthonous terranes in central Minnesota.  
Anderson, G.G.
34. 3:50 LaBerge, G. Was the Penokean orogeny a bi-polar event?  
Klasner, J.
35. 4:10 Turek, A. Advances in geochronology of the Michipicoten  
Sage, R.P. greenstone belt.  
van Schmus, W.R.

**SATURDAY, MAY 12**

**Field Trips 1, 2, 3 and 4**

*All field trips depart at 8 a.m. from the rear parking lot of the Airplane Motor Hotel. Lunch is provided.*

**TRIP NO. 1\*** R. Sutcliffe (leader) - Mafic intrusions, PGE mineralization and granitoid rocks of the Lac des Illes area.

**VANS**

**FOR PEOPLE WHO HAVE GONE ON TRIP NO. 4**

**TRIP NO. 2\*** G. Borradaile (leader) - Geology of the Shebandowan and Quetico Archean Subprovinces.

**VANS**

**TRIP NO. 3** S. Kissin (leader) - Granitoid related mineral deposits in the western Lake Superior region.

**BUS**

**TRIP NO. 4\*** M. Lavigne and J. Scott (leaders) - Base metal mineralization in the Shebandowan Greenstone Belt.

**BUS**

**FOR PEOPLE WHO ARE NOT GOING ON TRIP 1**

*All trips terminate at the Airplane Motor Hotel.*

\* Indicates trips which have been duplicated, (i.e. pre-meeting and post-meeting).

## POSTER PAPERS

Authors are requested to be present at their posters during the scheduled times from 1:00 to 1:30 on Thursday and Friday, and at other times when convenient.

1. Bauer, R.L. and Tabor, J.R.  
Syntectonic, intermediate-pressure regional metamorphism along the northern margin of the Quetico Belt in northeastern Minnesota: Contrasts with adjacent boundary areas.
2. Bennett, G., Born, P. and Hatfield, K.  
A recently discovered dolostone unit near Sault Ste. Marie, Ontario
3. Dahl, D.A. and Cartwright, D.F.  
Carbonate in till units of Lake of the Woods County, Minnesota.
4. Davidson, D.M., Jr.  
Magnetic susceptibility anisotropy and strain, Thomson formation (Proterozoic), Minnesota.
5. Feeney, J.\* and Kean, W.F.  
Paleomagnetism of Keweenaw age basalts of the Chengwatana volcanic group in the St. Croix Falls and Fredrick-Miltown area of Polk County, Wisconsin.
6. Geerts, S.D.\*  
Geology and mineralization in the Dunka Road copper-nickel mineral deposit, St. Louis County, Minnesota.
7. Jiran, J.  
State of Minnesota drill core library.
8. Johnson, R.C.\*  
Structure of the northern block of the Ishpeming Greenstone Belt, Marquette County, Michigan.
9. Mancuso, J., Stephen, J.\* and Kangas, W.  
Stratigraphy of the Negaunee Iron Formation, eastern Marquette Range, Michigan.
10. Milkereit, B. et al.  
Crustal structure of northeastern Lake Superior from GLIMPCE reflection and refraction data.

11. Mohn, P.A.\* and Gregg, W.J.  
Mesoscopic evidence for B<sub>1</sub> deformation in lower Proterozoic supracrustal rocks near Rockford, South Dakota.
12. Morton, R.L., Hudak, G.J., Walker, J.S. and Franklin, J.M.  
The physical volcanology and hydrothermal alteration associated with the massive sulphide deposits of the South Sturgeon Lake area, northwestern Ontario.
13. Mudrey, M.G., Dickas, A.B., McGinnis, L.D. and Cannon, W.F.  
Tectonic ramifications of GNI/Argonne Lake Superior seismic data.
14. O'Brien, M.  
Exploration and mining activity in northwestern Ontario.
15. Palmquist, J.C.  
Archean and Penokean strains in the Northern Complex, Marquette Mineral District, Michigan.
16. Saja, D.\* and Gregg, W.J.  
Structural studies in the Huron Bay parautochthon, Upper Michigan.
17. Severson, M.J.\* and Hauk, S.A.  
Geochemistry of unmineralized rocks in the Partridge River Intrusion, Duluth Complex.
18. Shurr, G., Watkins, I., Victory, D.\* and Tozer, M.\*  
Geological significance of linear features visible on Landsat images in west-central Minnesota.
19. Smith, M.  
Bioturbation in the Jacobsville sandstone, Lake Linden location - what are the implications?
20. Thompson, M.E., Ervin, C.P., Mudrey, M.G. and Brown, B.A.  
Tectonic ramifications of GNI/Argonne Lake Superior seismic data.

*Informal displays by:*

- a. Jirsa, M.A., Boerboom, T. and Southwick, D.
- b. Zayachivsky, B. Ontario Geological Survey.

## ABSTRACTS

## Geology of the Shebandowan Mine

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The Shebandowan Mine, owned by Inco Limited and operated by MacIsaac Explorations, is the only producing Nickel Copper mine in northwestern Ontario. It is located 75 km west-northwest of Thunder Bay.

The geology of the mine property consists of Keewatin mafic volcanics and ultramafics unconformably overlain by Timiskaming type volcanics and sediments. All are intruded by granitic rocks of the Shebandowan Lake Stock. The Crayfish Creek Fault is a major transcurrent fault that crosses the property, just south of the Shebandowan mine.

The sulphide mineralization at Shebandowan consists primarily of stringer, breccia and massive sulphides hosted by sheared and faulted peridotite. The main sulphides are pyrrhotite, chalcopyrite and pentlandite. The sulphides show evidence of remobilization due to dynamic metamorphism.

Other ultramafics in the immediate area provide evidence that they are komatiite flows rather than sills as previously believed. The Shebandowan nickel-copper deposit has many physical similarities to the Redross deposit in Australia, a dynamically metamorphosed nickel-copper sulphide deposit hosted by a komatiite flow. It is postulated that the Shebandowan Ni-Cu mine is also the product of a deformed and remobilized komatiite hosted sulphide deposit.

SYNTECTONIC, INTERMEDIATE-PRESSURE REGIONAL METAMORPHISM ALONG  
THE NORTHERN MARGIN OF THE QUETICO BELT IN NORTHEASTERN MINNESOTA:  
CONTRASTS WITH ADJACENT BOUNDARY AREAS

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Metamorphism in the schist and migmatite along the northern margin of the Quetico belt is typically post to late tectonic and shows high lateral thermal gradients adjacent to high-level plutons of the region (Percival, 1989). Pirie and Mackasey (1978), for instance, described a 4 km transition from the chlorite zone progressively through the biotite, garnet, andalusite, garnet-sillimanite, garnet-cordierite-sillimanite, and migmatite zones in the country rocks north of the Sturgeon Lake batholith (assemblages 1-15 in Fig. 1). Similar low-pressure zonal sequences and high geothermal gradients over distances of less than 6 km have been reported from several localities in the central Quetico belt (Pirie and Mackasey, 1978; Sawyer, 1983) and from the area east of Lake Nipigon (Percival, 1983; Pirie and Mackasey, 1978).

In contrast to these studies, our work along the northern margin of the belt, southeast of International Falls and west of the Sturgeon Lake batholith (SLB), indicates that the schist and migmatite of this area have undergone syntectonic, intermediate-pressure metamorphism that apparently predates the lower pressure, posttectonic metamorphism along the belt margin to the east. The metamorphism in our study area displays a Barrovian zonal series, ranging from the kyanite-staurolite zone to the cordierite - K-feldspar zone (Table 1; assemblages I-VI in Fig. 1). The thermal event peaked during the second of three periods of folding that deform the schist and migmatite of the area (Bauer, 1988). Fibrolite tufts from the sillimanite-staurolite zone through the sillimanite - K-feldspar zone are aligned parallel to an  $S_2$  foliation and are folded by  $F_3$  folds and an  $S_3$  crenulation foliation. Cordierite porphyroblasts locally contain  $F_2$ -folded inclusion trails of sillimanite and are elongated parallel to a strong  $L_3$  lineation that was accentuated by the nearly coaxial nature of the  $F_2$  and  $F_3$  regional fold systems.

Randomly oriented blocky crystals of retrograde muscovite locally replace K-feldspar and sillimanite and may contain inclusion trails of  $F_3$ -folded sillimanite. The retrograde muscovite and the common partial replacement of garnet by biotite + sillimanite suggest a decompression cooling path for the rocks during and following  $F_3$  folding.

Although porphyroblast growth in the areas of steep thermal gradient north of the SLB is typically post  $D_1$  and  $D_2$ , Kehlenbeck (1976) found evidence for a polymetamorphic history with both syntectonic and posttectonic porphyroblast growth in the rocks north of the SLB north of Thunder Bay. He suggested that either contact or low-pressure regional metamorphism was overprinted on pre-existing regionally metamorphosed rocks in this area. We believe that the syntectonic metamorphism we see in the schist west of the Sturgeon Lake batholith may be correlated with the syntectonic event described by Kehlenbeck (1976).

## REFERENCES CITED

- Bauer, R.L., 1988, Multiple folding and regional fold patterns in the northern Vermilion Granitic Complex, N.E. Minnesota: Institute on Lake Superior Geology, Proceedings and Abstracts, V. 34, p.3.
- Kehlenbeck, M.M., 1986, Nature of the Quetico - Wabigoon boundary in the de Courcey-Smiley Lakes area, northwestern Ontario. Canadian Journal of Earth Sciences, v. 13, p. 737-748.
- Pirie, J.A. and Mackasey, W.O., 1978, Preliminary examination of regional metamorphism in parts of the Quetico metasedimentary belt, Superior Province, Ontario. In Metamorphism in the Canadian shield. (edited by) J.A. Fraser and W.W. Heywood, Geological Survey of Canada, Paper, 78-10, p. 37-48.
- Percival, J.A., 1983, Preliminary results of geological synthesis in the western Superior Province. In Current Research, part A. Geological Survey of Canada, Paper, 83-1a, p. 125-131.
- Percival, J.A., 1989, A regional perspective of the Quetico metasedimentary belt, Superior Province, Canada. Canadian Journal of Earth Sciences, v. 26, p. 677-693.
- Sawyer, E.W., 1983, The structural history of a part of the Archean Quetico metasedimentary belt, Superior Province, Canada. Precambrian Research, v. 22, p. 445-473.

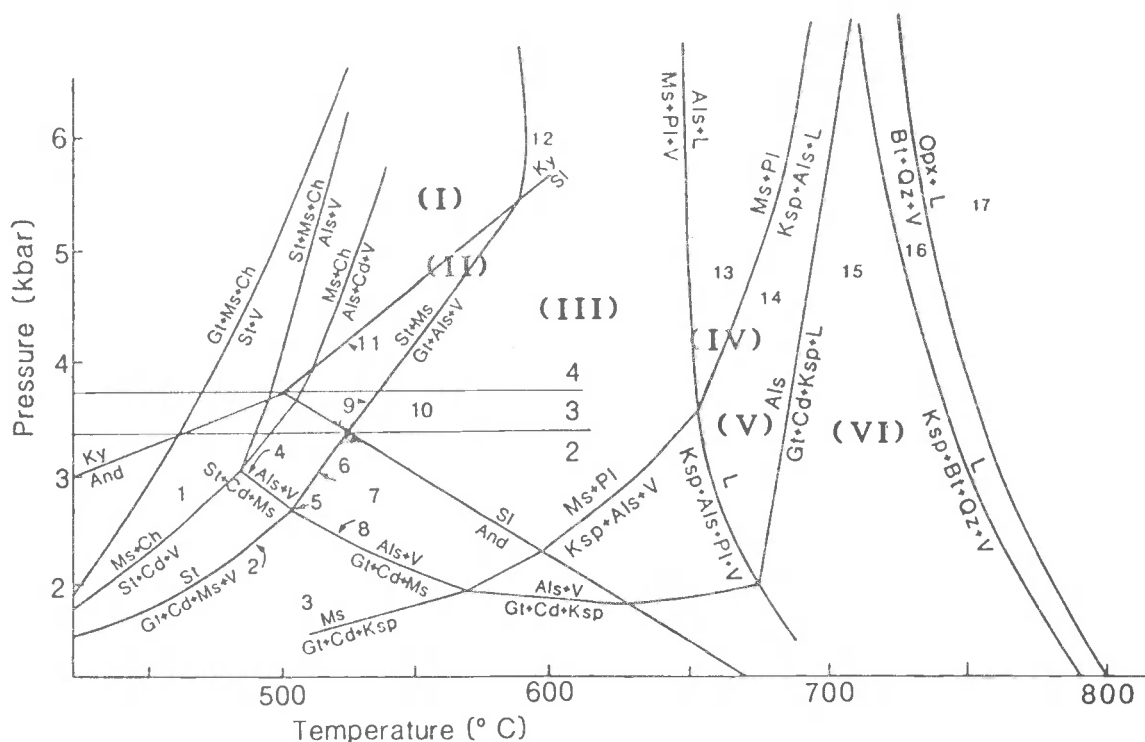


**Fig. 1** Petrogenetic grid showing the stability fields of mineral assemblages in pelitic, migmatitic, and granitic rocks at medium and high grades (from Percival, 1989). The small numbers correspond to mineral assemblages in the metamorphic zones in the vicinity of the Sturgeon Lake batholith. The large numbers indicate bathozones 2, 3, and 4 of Charnmichael, (1978). The Roman numerals indicate the metamorphic zones in our study area west of the Sturgeon Lake batholith.

Table 1. Metamorphic zones, associated mineral assemblages and reactions

| Zone | Mineral Assemblage         | Zone Reaction                                     |
|------|----------------------------|---------------------------------------------------|
| I    | ky-st-gt-mu-bi-pl-qz-il    |                                                   |
|      |                            | ky = sill                                         |
| II   | sill-st-gt-mu-bi-pl-qz-il  |                                                   |
|      |                            | st + mu + qz = sill + gt + bi + H <sub>2</sub> O  |
| III  | sill-mu-gt-bi-pl-qz-il     |                                                   |
| IV   | ksp-mu-sill-gt-bi-pl-qz-il | mu + pl + qz = sill + ksp + H <sub>2</sub> O      |
| V    | ksp-sill-gt-bi-pl-qz-il    |                                                   |
|      |                            | sill + bi + qz = cd + gt + ksp + H <sub>2</sub> O |
| VI   | cd-ksp-gt-sill-bi-pl-qz-il |                                                   |

Mineral Abbreviations

|                 |                  |                    |
|-----------------|------------------|--------------------|
| bi - biotite    | il - ilmenite    | pl - plagioclase   |
| cd - cordierite | ksp - k-feldspar | qz - quartz        |
| gt - garnet     | ky - kyanite     | sill - sillimanite |
|                 | mu - muscovite   | st - staurolite    |

A RECENTLY DISCOVERED DOLOSTONE UNIT  
NEAR SAULT STE. MARIE, ONTARIO.

G. Bennett, Ministry of Northern Development and Mines  
Sault Ste. Marie, Ontario; P. Born, Ministry of Northern  
Development and Mines, Toronto; K. Hatfield, Lake Superior  
State University, Sault Ste. Marie, Michigan

Born (1987) reported a previously unrecognized occurrence of dolostone in Fenwick Township, approximately 27 km northwest of Sault Ste. Marie, Ontario.

The area is not well exposed, but detailed mapping indicates that the dolostone and associated rocks probably form an east-west trending fault block, bounded on the south by the Lorrain Formation of the Huronian Supergroup and by Archean rocks on the north. The total thickness of the exposed dolostone unit is at least 30 meters. The lowermost one third of the dolostone sequence consists mainly of very fine-grained, pale pink to reddish pink dolostone and intercalated grey to pink metachert. Individual dolostone beds are from a few millimeters to at least a meter thick. The metachert beds have a similar thickness range but form less than 25 percent of the visible section.

Pale grey, clastic dolostone is most abundant type in the upper part of the carbonate unit. This calcarenite consists of variable proportions of angular to subrounded sand-sized clasts of fine-grained dolostone and subrounded to well-rounded quartz grains. Well developed oolites are locally present. The clastic dolostone generally forms thick beds separated by thin beds of fine grained dolostone or chert. Coarse, pink coloured barite locally occurs as a few lensoid masses up to 50 cm across.

No clearly identifiable stromatolites were observed in the dolostone of Fenwick Township but irregular, wavy, laminae of brownish chert, suggestive of algal mats, are locally present.

The clastic dolostone is directly overlain by deep red sandstone, and red to pink laminated siltstone. The contact between the red beds and the dolostone is abrupt and concordant. The dolostone unit directly overlies highly fractured and sheared, locally laminated, green and maroon siltstone and argillite. A few beds of recrystallized chert, at least 20 cm thick and one dolostone bed of similar

thickness, was observed within the siltstone.

The presence of red beds above and below the dolostone unit, and the degree of metamorphism and deformation indicates that the dolostone is post-Quirke Lake Group (Huronian) and pre-Keewenawan.

The only known dolostone in the general area within the above constraints is found in the Gordon Lake Formation of the Huronian Supergroup (Hofmann et al. 1983). A variety of sedimentary features indicate the Gordon Lake Formation was deposited in a shallow, active water environment such as a tidal flat (Wood, 1973, p. 91). The recognition of nodules of gypsum and anhydrite in the Gordon Lake Formation indicates local evaporitic conditions (Wood, 1973, p. 85). The presence of oolites and sulphate (barite) in the dolostone of Fenwick Township indicates a similar depositional environment to that proposed for the Gordon Lake Formation.

There has been a long standing debate as to stratigraphic equivalence of the Huronian rocks of Ontario and the Middle Precambrian rocks of the Lake Superior region. The lithological and stratigraphic similarities of the Chocoma Group (and equivalent groups further west) and the Cobalt Group of the Huronian of Ontario have been pointed out by Church and Young (1970), Young (1983) and Cannon (1975). However, this time-stratigraphic correlation has not been widely accepted (e.g. Morey 1973, p. 242-244, and Card 1978, p. 24) since radiometric dating of rocks, considered to underlie the Chocoma group, provide evidence that the Chocoma Group is younger than the Huronian Supergroup of Ontario.

The dolostone of Fenwick Township very closely resembles, both lithologically and stratigraphically the Kona Dolomite and equivalent units of the Marquette Range Supergroup.

#### REFERENCES CITED

- Born, P.  
1987: Geology of the Havilland-Goulais Bay Area, District of Algoma; Ontario Geological Survey, O.F.R. 5602, 114p., 11 figures, 7 tables, 12 photos, and 3 maps in back pocket.
- Cannon, W. F.  
1975: Basal Conglomerates and Weathered Zones in the Marquette Range Supergroup, Northern Peninsula of

Michigan - Age, indications of atmospheric oxygen, and uranium potential, p. Z1-Z17, in Genesis of Uranium- and Gold-Bearing Precambrian Quartz-Pebble Conglomerates, Geological Survey Professional Paper 1161 - A - BB, edited by Frank C. Armstrong, United States Government Printing Office, Washington.

Card, K. D.

1978: Geology of the Sudbury-Manitoulin Area, Districts of Sudbury and Manitoulin; Ontario Geological Survey Report 166, 238p. Accompanied by Map 2360, scale 1 inch to 2 miles (1:126,720), and 4 charts.

Church, W. R., and Young, G. M.

1970: Discussion of the progress report of the Federal-Provincial Committee on Huronian stratigraphy: Canadian Journal of Earth Sciences, v. 7, p. 912-918.

Hofmann, H. J., Pearson, D. A. B., and Wilson, B. H.

1980: Stromatolites and fenestral fabric in early Proterozoic Huronian Supergroup, Ontario: Canadian Journal of Earth Sciences, v. 17, p. 1351-1357.

Morey, G. B.

1973: Stratigraphic framework of middle Precambrian rocks in Minnesota, in Young, G. M., ed., Huronian stratigraphy and sedimentation, Minnesota, in Young, G. M., ed., Huronian stratigraphy and sedimentation, Geological Association of Canada Special Paper 12, p. 211-249.

Wood, J.

1973: Stratigraphy and depositional environments of upper Huronian rocks of the Rawhide Lake-Flack Lake area, Ontario, in Young, G. M., ed., Huronian stratigraphy and sedimentation: Geological Association of Canada Special paper 12, p. 73-95.

Young, G. M.

1983: Tectono-sedimentary history of early Proterozoic rocks of the northern Great Lakes region, p. 15-32; in Geological Society of America Memoir 160, Edited by L. G. Medaris, Jr.

Magnetic Survey of the Niagara Fault System  
in Northeastern Wisconsin and Northwestern  
Upper Peninsula Michigan

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The Niagara fault system has been identified based on magnetic data. One of the first ground magnetic surveys of the Niagara fault system was conducted on a four square mile area near Keyes Lake by Weir and Solberg in 1958-59 using vertical intensity magnetometers. Since that time, several aeromagnetic surveys have been flown across the area in an attempt to further define the extent and trend of the system. This ground magnetic study was undertaken in combination with a paleomagnetic study of the area in order to fully detail the trend of the system and to unravel the tectonic history of the area.

Two hundred thirty seven miles of field magnetic data were collected using two EG&G proton procession magnetometers. One magnetometer was used as a continually recording base station. The second magnetometer was used to collect readings at .1 mile spacings. The survey area was confined to Florence, Marinette, Dickinson, and Menominee counties Wisconsin and Michigan (Fig. 1). The data was modeled on a computer. The model parameters of susceptibility, remnant component intensity, and direction were determined from laboratory and paleomagnetic analysis of samples obtained in the field along survey lines. In areas where outcrops were not available along survey lines, similar units from other outcrops within the study area were used. Model parameters of length of lithologic or lithodemic unit, depth of unit, and strike half-length were obtained from maps. Because the maps are based on outcrops, and outcrops are sparse, the length, depth and strike half-length of the units were adjusted as needed.

The ground magnetic results indicate that the Niagara Fault does not trend the way it is represented on the Wisconsin Northeast sheet map (Greenberg and Brown, 1984). The data points were upward continued to 500 feet and the individual anomalies produced by the faults merged with the regional magnetics and produced small elliptical highs. The peaks of these highs did not necessarily coincide with the location of the anomalies produced by the faults. The new trend of the faults are based on the individual fault anomalies. Modeling results produced only a few tectonic settings for the area.

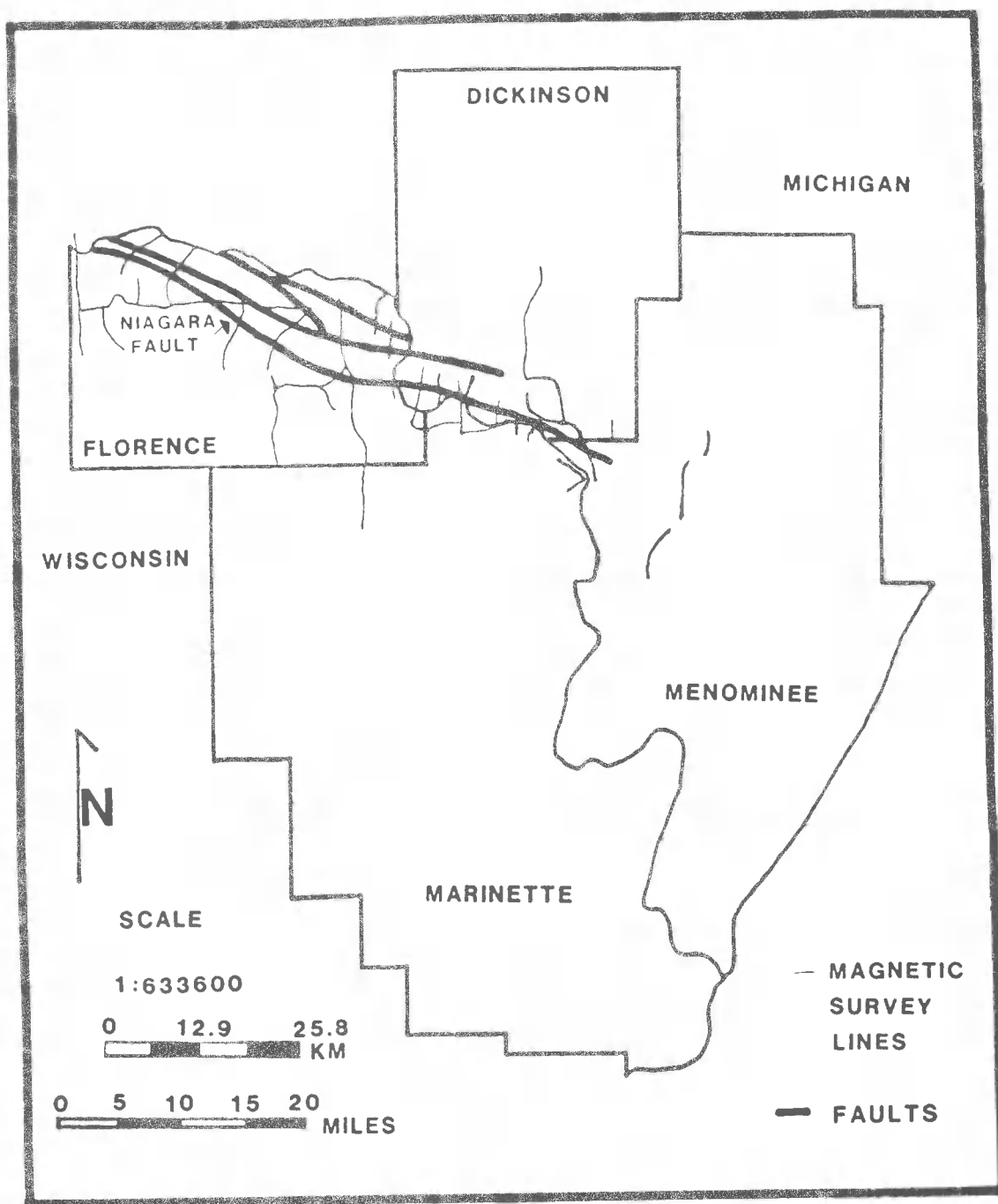


**Figure 1.** Map indicating field magnetic survey lines. Modified from Greenberg and Brown, 1984; and Champion International Corporation, 1986.

## **PARTICULATE FLOW AND THE DEFORMATION OF ROCK: FIELD AND EXPERIMENTAL RESULTS**

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Field evidence from low-grade metasedimentary rocks and from tectonically deformed sediments often shows a discrepancy between strains determined on large and small scales. Large scale strains (hand-specimen to many kilometres) are often higher than the strains of small sedimentary structures or individual clastic grains. When grain-scale strain is removed mathematically from a large structure, it is imperfectly "de-strained" because considerable large scale distortion may remain.

It is postulated that much of this missing strain is taken up by interparticle motion which remains elusive to petrographic examination. Thus clastic grains only record part of the strain history while much strain is taken up by intergranular displacements. This involves displacements on multigranular boundaries and, being more encompassing than grain-boundary sliding, it is termed "particulate flow".

Recent high pressure experimental work has confirmed that particulate flow is enhanced by high pre-fluid pressures. These support some of the load so that the intergranular contact stresses are reduced ("effective stresses") and slippage within the rock mass is eased. These experiments also confirm that grain deformation is reduced by this process (e.g. twinning in calcite is less severe) and fluid pressure oscillates as groups of grains slide past one another producing ephemeral volume changes within the specimen. A further consequence of the experiments is that the bulk strain exceeds the grain-scale strain as the field evidence shows. This effect is greater at high pore fluid pressures.

### REFERENCES

- Borradaile, G.J., 1981. Particulate flow and the formation of rock cleavage. *Tectonophysics*, 72: 305-321.
- Borradaile, G.J. and McArthur, J., 1990. Experimental calcite aggregates in a synthetic weaker matrix by coaxial and non-coaxial deformation. *J. Structural Geology*, In Press.

# STRUCTURAL AND ISOTOPIC EVIDENCE FOR MIDDLE PROTEROZOIC THRUST FAULTING OF ARCHEAN AND EARLY PROTEROZOIC ROCKS NEAR THE GOGEBIC RANGE, MICHIGAN AND WISCONSIN

William F. Cannon, US Geological Survey, Reston, VA  
Zell E. Peterman, US Geological Survey, Denver, CO  
Paul K. Sims, US Geological Survey, Denver, CO

Faults with substantial reverse displacement in the Midcontinent Rift, such as the Keweenaw and Lake Owen Faults (Figure 1), have been well documented. They offset most units of the Keweenaw Supergroup but appear to be truncated by the youngest units in places, thereby dating the fault motion approximately in the interval 1.1-1.0 Ga. An additional fault or set of faults, herein called the Marenisco Fault, is a previously unrecognized companion to the Keweenaw and Lake Owens Faults and offsets Archean and Early Proterozoic rocks across a belt as much as 30 km wide south of the Keweenaw Fault near the Gogebic Iron Range.

The existence of Keweenaw or younger deformation in some of the Archean and Early Proterozoic rocks in this belt is well documented. Keweenaw and Early Proterozoic rocks along the Gogebic Range form an unconformable but structurally concordant unit that is tilted northward along with at least some of the Archean basement, but the kinematics and regional extent of this tilting have remained obscure.

We have used the orientation of Keweenaw and Early Proterozoic diabase dikes as structural markers to address these questions. The analysis is based on the assumption that the dikes were emplaced nearly vertically and that the Early Proterozoic dikes were not appreciably deformed prior to Keweenaw time. Regional relations support both assumptions. We have located about 45 outcrops, mostly Archean rocks, where we could measure orientations of diabase dikes (see figure 1). Most dikes have a southward component of dip indicating northward tectonic rotation since emplacement. In some of the southernmost outcrops the dikes remain nearly vertical and thereby provide a southern limit to the rotated area. In Michigan, the dikes form an orthogonal system and it is possible to determine a unique direction and amount of rotation that transposed both sets from vertical to their present orientation. Figure 1 shows the amount and direction of rotation for four areas where they are best constrained. The rotation is not uniform and varies from 25 to 60 degrees suggesting either multiple fault blocks or broad folding.

Rb-Sr ages of biotite from Archean and Early Proterozoic rocks (see Figure 1) help to resolve the mechanism of deformation and indicate that northward tilting was accompanied by uplift of the tilted blocks. Biotite ages within the area containing rotated dikes are close to the ages of Keweenaw events, whereas older biotite ages occur where the dikes maintain their vertical orientation. The blocking temperature for the Rb-Sr biotite system is thought to be between 250 and 300 degrees C, varying slightly as a function of cooling rate. When rocks are uplifted from depths where the ambient temperature exceeds 250-300 degrees and cooled rapidly, the biotite ages approximate the time of uplift. We

interpret the biotite ages (1.0-1.1 Ga) in the zone of rotation as recording such uplift and cooling during late Keweenawan thrust faulting. Older biotite ages outside of this zone record an earlier cooling event probably associated with stabilization following the Penokean orogeny.

Figure 2 shows our interpretation of the structural and isotopic data. Figure 2a portrays the geometry at the onset of faulting and during deposition of the Jacobsville Sandstone. Fanning relationships within the thick sequence of Keweenawan basalts, and unconformable relationships of the Jacobsville indicate that rotation toward the rift of 15-30 degrees occurred during volcanism and deposition of the Oronto Group. We interpret this as flexing in response to crustal thinning and emplacement of the load of volcanic and sedimentary rocks. At this time the isotherm of the Rb-Sr blocking temperature for biotite was a nearly horizontal surface. Figure 2b. shows the present geometry. The listric nature of the Marenisco Fault has caused about 30 degrees of additional northward rotation of Archean and Early Proterozoic rocks as well as the Keweenawan sequence. Southward thrusting on the order of 10 km is sufficient to account for the present geometry. North of the Marenisco Fault the blocking isotherm has been rotated, uplifted, and exposed by erosion. Within area a of Figure 2b biotite ages record the uplift event. In areas b and c, rocks now at the surface remained above the blocking isotherm and biotite ages still reflect older events.

In summary, isotopic and structural data indicate that thrust faults related to reverse faults within the Midcontinent Rift extend for tens of kilometers outside of the rift. Part of the Marenisco Fault has been mapped previously, but was interpreted to be of Archean or Early Proterozoic age. Structural analysis of older rocks elsewhere near the Midcontinent Rift should account for the possibility of Middle Proterozoic deformation superimposed on Archean or Early Proterozoic structures.

#### References

- Prinz, William C., 1981, Geologic map of the Gogebic Range-Watersmeet area, Gogebic and Ontonagon Counties, Michigan: U.S. Geological Survey Miscellaneous Investigations Map I-1365, scale 1:125,000.
- Peterman, Z. E., Zartman, R. E., and Sims, P. K., 1980, Tonalitic gneisses of early Archean age from northern Michigan, *in* Selected studies of Archean and Lower Proterozoic gneisses, G.B. Morey and G. N. Hanson (eds.): Geological Society of America Special Paper 182, p. 125-134.
- Peterman, Z. E. and Sims, P. K., 1988, The Goodman swell: a lithospheric flexure caused by crustal loading along the Midcontinent Rift System, *Tectonics*, v. 7, p. 1077-1090.
- Sims, P. K., (in press), Geologic map of Precambrian rocks in Wisconsin and northern Michigan: U.S. Geological Survey Miscellaneous Investigations Map, scale 1: 500,000.



## THE PALEOMAGNETISM OF THE EARLY PROTEROZOIC SIOUX QUARTZITE, SOUTHWESTERN MINNESOTA

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Paleomagnetic studies were conducted on the Early Proterozoic Sioux Quartzite of southwestern Minnesota, a sequence of hematite- and silica-cemented quartz arenites that were deposited by fluvial processes in several elongate depobasins bounded by northwest-trending faults. A total of 158 samples of quartz arenitic material were collected from 17 sites scattered across four basins (Cottonwood County, New Ulm, North Pipestone, and South Pipestone).

As judged from alternating-field (AF) and thermal demagnetization studies, the magnetization is dominantly single-component, and as judged from high coercivities and blocking temperatures, the magnetic carrier is hematite. A definitive fold test is difficult to perform, because cross beds obscure gently dipping master bedding features. Nonetheless, most of the magnetization seems to have occurred before a period of regional-scale tilting that formed the basins. Measured paleomagnetic directions at both site and basin levels show good clustering, and the average directions obtained from each of the four basins are not significantly different at the 95% confidence level. After the effects of regional tilting were removed, the paleomagnetic directions from the four basins yield a combined paleopole located at  $101^{\circ}\text{W.}$  and  $16^{\circ}\text{N.}$  ( $k=65$ ,  $a95=11^{\circ}$ ).

After AF demagnetization, clasts from a basal conglomerate in the New Ulm basin show a paleomagnetic bias in the direction of that observed in the overlying quartzite, implying post-depositional magnetization. Furthermore, hematite, the primary magnetic carrier in the Sioux, occurs as a diagenetic mineral with a long paragenetic history (Southwick and others, 1986; Vander Horck, 1984) and, in the case of the North Pipestone basin, also as veinlets that formed during a strain event (Morey, 1984) that may have been related to regional tilting.

On the Early Proterozoic apparent polar wander curve of Irving (1979) the Sioux paleopole lies along the 1700-1650 m.y. segment, which corresponds in part with the time of the Central Plains orogen of Sims and Peterman (1986) of 1800-1630 m.y. The Sioux outcrops are located only some 200-300 km north of rocks clearly involved with the Central Plains orogen (Fig. 1), and Southwick and others (1986) have tentatively suggested that the northwest-trending faults that bound the individual Sioux basins were related to the orogen. Conversely, the Sioux Quartzite could have been deposited at some time well before the orogen and subsequently modified by tectonic processes associated with the orogen. In the first situation the paleomagnetic pole position would reflect diagenetic processes that may have closely followed sedimentation, whereas in the second, it would reflect a period of secondary overprinting that would have involved wholesale recrystallization of hematite. There is no obvious evidence that the hematite in the Sioux, except for that in veinlets, has been recrystallized. We therefore suggest that it is more likely that the magnetization we observe is primarily related to diagenetic processes. Although considerable uncertainties still exist, our results are consistent with the conclusions of Morey and Van Schmus (1980), who suggested that the so-called "Baraboo interval quartzites at the Lake Superior region" were deposited during the interval 1760-1630 m.y.

### References Cited

- Irving, E., 1979, Paleopoles and paleolatitudes of North America and speculations about displaced terrains: *Canadian Journal of Earth Sciences*, v. 16, p. 669-694.  
Morey, G.B., 1984, Sedimentology of the Sioux Quartzite in the Fulda basin, Pipestone County, southwestern Minnesota, *in* Southwick, D.L., ed., *Shorter contributions to*

- the geology of the Sioux Quartzite (early Proterozoic), southwestern Minnesota: Minnesota Geological Survey Report of Investigations 32, p. 59-74.
- 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.
- Sims, P.K., and Peterman, Z.E., 1986, Early Proterozoic Central Plains orogen: A major buried structure in the north-central United States: *Geology*, v. 14, p. 488-491.
- Southwick, D.L., Morey, G.B., and Mossler, J.H., 1986, Fluvial origin of the lower Proterozoic Sioux Quartzite, southwestern Minnesota: *Geological Society of America Bulletin*, v. 97, p. 1432-1441.
- Vander Horck, M.P., 1984, Diagenesis in the Sioux Quartzite: Unpub. M.S. thesis: University of Minnesota, Minneapolis, 101 p.

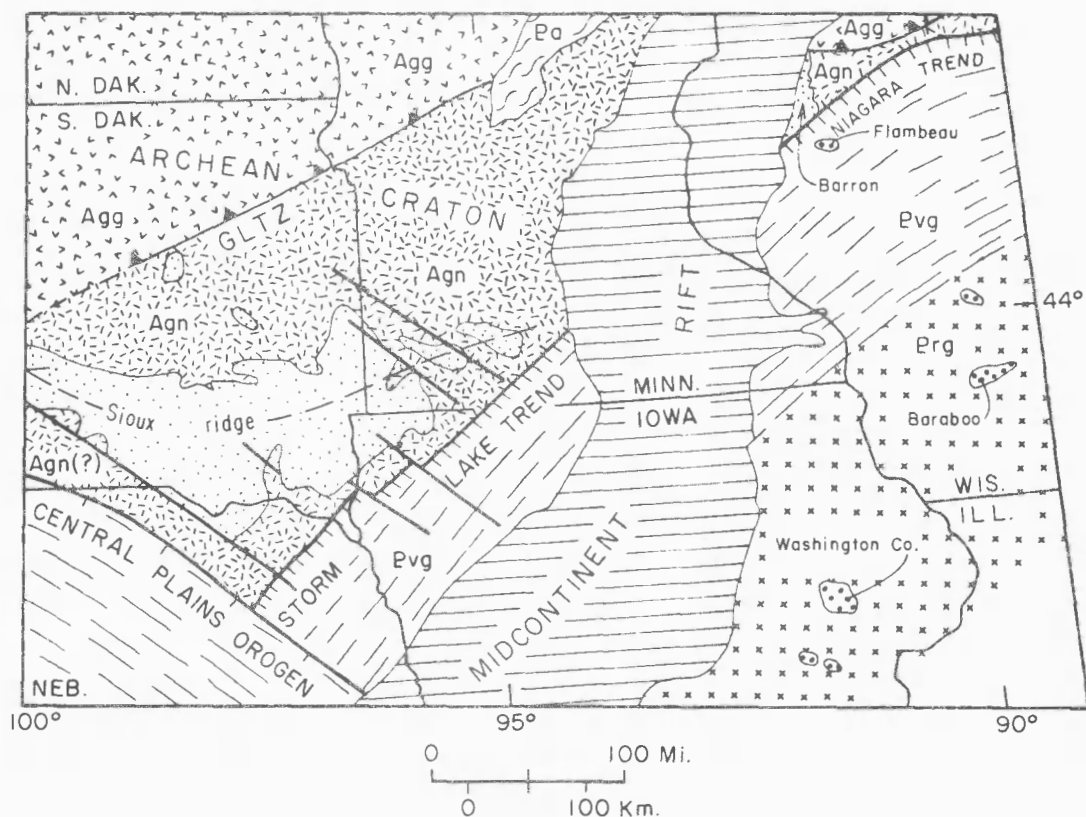


Figure 1. Generalized geologic map of the central plains region (from Southwick and others, 1986).

# CARBONATE IN TILL UNITS OF LAKE OF THE WOODS COUNTY, MINNESOTA

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## ABSTRACT

Within Lake of the Woods County, carbonate content and matrix solubility are being used, among other quantitative methods, to characterize the glacial drift that overlies Archean bedrock.

Bedrock in this northwestern Minnesota county is distributed as a belt of Archean supracrustal rocks bounded on the north and east by granitic intrusives and bounded on the south by faulted contact with gneisses of the Quetico meta-sedimentary subprovince. The supracrustal sequence is masked by sedimentary cover (overburden) which ranges in thickness from 60 to 300 feet.

As part of a project to encourage exploration in areas of deeper glacial drift (as is the case in Lake of the Woods county), MnDNR is conducting an overburden drilling project to characterize the regolith (glacial drift and saprolite) of the area in terms of its feasibility for use as an exploration medium.

Three packages of glacial drift have been recognized beneath the surficial Koochiching lobe sediments during descriptive logging of core taken from twenty rotasonic drill holes drilled in twenty townships during the fall of 1989. Matrix solubility and carbonate pebble content of till units within the drift packages are being used along with textural analysis and trace metal measurements to develop a framework by which the sub-Koochiching drift may be quickly and accurately differentiated during exploration drilling.

One hundred and forty samples of the -63 $\mu$ m (silt-clay) component of sub-Koochiching tills were leached in 4N HCl to dissolve any carbonate in the samples. Weights of insoluble residue were measured and Ca, Mg, and Fe in the soluble portion were analyzed by atomic absorption spectroscopy. Matrix solubilities range from 3 to 54 percent and fall into three distinct sub-populations. These sub-populations compare well to subdivisions recognized qualitatively during descriptive logging. Pebble counts of the coarse (5-15mm) component of the till samples also reflect these distinctions.

Characteristic recognition of the range, median, and variability of the carbonate content and matrix solubility of the sub-Koochiching drift packages will provide a framework for recognizing till units and for resolving intra-till compositional variations such as contamination by underlying drift units and incorporation of siderite/carbonate from underlying saprolite.

MAGNETIC SUSCEPTIBILITY ANISOTROPY  
AND STRAIN, THOMSON FORMATION (PROTEROZOIC),  
MINNESOTA

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Four samples of the Proterozoic Thomson Formation have been analyzed using a Sapphire Instrument Model SI-2 magnetic susceptibility bridge. Oriented bulk samples were collected from a fold exposed north of Carlton, Minnesota, well within the "northern area" interpreted by Holst (1984) to have undergone but one phase of Penokian deformation. The purpose of the study was to evaluate the suitability of susceptibility anisotropy as a measure of deformation magnitude and orientation using these samples.

Natural Strain Data:

Holst (1985) has presented strain data for the area based on measurements of deformed concretions and mudchips. Similar data collected by me only for "whole" concretions are also presented.

| Holst ( $n \geq 100$ ) |      |      |      |      | a    | b    | $\Sigma_1 - \Sigma_2$ | $\Sigma_2 - \Sigma_3$ | k    | K    |
|------------------------|------|------|------|------|------|------|-----------------------|-----------------------|------|------|
| 1                      |      |      |      |      | 1.55 | 3.92 | 0.44                  | 1.37                  | 0.19 | 0.32 |
| 2                      |      |      |      |      | 1.39 | 5.84 | 0.33                  | 1.76                  | 0.08 | 0.19 |
| 3                      |      |      |      |      | 1.62 | 4.35 | 0.48                  | 1.47                  | 0.19 | 0.33 |
| Average                |      |      |      |      | 1.52 | 4.70 | .42                   | 1.53                  | 0.15 | 0.28 |
| Davidson               | n    | X    | Y    | Z    | a    | b    | $\Sigma_1 - \Sigma_2$ | $\Sigma_2 - \Sigma_3$ | k    | K    |
| STA 1/4                | (34) | 4.77 | 2.38 | 1.00 | 2.00 | 2.38 | .69                   | .87                   | .73  | .80  |
| STA 2                  | (15) | 4.70 | 2.30 | 1.00 | 2.04 | 2.30 | .71                   | .83                   | .80  | .86  |
| STA 3                  | (30) | 4.91 | 2.83 | 1.00 | 1.74 | 2.83 | .55                   | 1.04                  | .40  | .53  |
| STA 5                  | (10) | 6.27 | 3.19 | 1.00 | 1.97 | 3.19 | .68                   | 1.16                  | .44  | .58  |
| STA 8                  | (14) | 4.20 | 2.36 | 1.00 | 1.78 | 2.36 | .57                   | .86                   | .57  | .75  |
| Average                |      | 4.97 | 2.61 | 1.00 | 1.91 | 2.61 | .64                   | .95                   | .59  | .71  |

n=number of measurements

In this area, the X is vertical and Z is N-S and horizontal; hence concretions are flattened within a well-developed vertical cleavage.

## Magnetic Susceptibility Anisotropy:

Right cylinders were cut from the oriented samples and 24 orientation measurements were made on each. Results to date are:

|             | EV( $\times 10^{-5}$ ) |      |      | SD<br>( $\times 10^{-5}$ ) | EV (MIN)        |     |     | CORE<br>ORIENTATION |     |
|-------------|------------------------|------|------|----------------------------|-----------------|-----|-----|---------------------|-----|
|             | MAX                    | INT  | MIN  |                            | R <sub>95</sub> | DEC | INC | DEC                 | INC |
| 1 Graywacke | 1.67                   | 1.62 | 1.5  | 1.3                        | 2.6             | 351 | 3   | 303                 | 79  |
| 1 Slate     | 3.80                   | 3.69 | 3.40 | 2.5                        | 6.4             | 351 | 1   | 303                 | 18  |
| 3 Graywacke | 3.66                   | 3.43 | 3.03 | 3.54                       | 2.7             | 350 | 5   | 18                  | 18  |
| 3 Slate     | 2.62                   | 2.59 | 2.49 | 2.61                       | 4.0             | 291 | 7   | 26                  | 19  |

## Interpretation

My natural strain data, although similar to the values derived by Holst (1985), consistently show higher X/Y and lower Y/Z strain values, hence larger k values. I attribute the differences to my limited number of measurements and to concretion behavior relative to measurements from 2d sections and deformed mud chips.

The magnetic anisotropy data are inconsistent, although the orientations of EV are quite close to similar values for natural strains. Sampling problems (e.g. near horizontal cores) are believed to contribute to the variations. Comparisons of strain and susceptibility magnitude appear premature given the limited data as well as the fact that these rocks are weakly strained and may have undergone pressure solution effects (Borradaile, 1988).

## References

- Borradaile, G.J., 1988, Magnetic susceptibility, petrofabrics and strain: Tectonophysics, 156, 1-20.
- Holst, T.B., 1984, Evidence for nappe development during the Early Proterozoic Penokian Orogeny, Minnesota: Geology 12, 135-138.
- \_\_\_\_\_, 1985, Implications of a large flattening strain for the origin of a bedding-parallel foliation in the Early Proterozoic Thomson Formation, Minnesota: Jour. Structural Geol. 7, 375-383.

# THE SEINE-COUTCHICHING PROBLEM RECONSIDERED: U-PB GEOCHRONOLOGICAL DATA CONCERNING THE SOURCE AND TIMING OF ARCHEAN SEDIMENTATION IN THE WESTERN SUPERIOR PROVINCE

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Clastic sediments in the Superior Province mostly fall into two categories: an alluvial fan-fluvial facies association of sandstone and conglomerate and a resedimented facies association of marine turbidite (Ojakangas 1985). Rocks of the resedimented facies association form the major proportion of Archean sediments and make up most of the supracrustal component of entire subprovinces such as the English River, Quetico and Pontiac. Alluvial sediments are relatively minor in volume and are generally exposed along faults either within greenstone belts or at the boundaries between subprovinces.

The relationship between these sediment types has been a focus for debate in Archean geology for over a century, beginning with the work of A.C. Lawson (1887, 1913) in the Rainy Lake area. Lawson argued that alluvial sediments (Seine Group) are much younger than turbidites in the area (Coutchiching Group). Others have since argued that they represent a transition from continental to marine depositional environments. Field relationships between these facies associations are generally complex. Transitional sedimentary facies are rare and in some cases turbiditic sediments overlie alluvial sediments, a relationship which is the opposite of what would be expected from a prograding alluvial fan.

It is now possible to measure concordant, precise ages on single detrital zircon grains and these studies afford new insight into the relationship between sedimentary facies and their role in the tectonic development of the Superior Province. The classic Seine-Coutchiching problem has been resolved in the Rainy Lake area. Detrital zircons in the Coutchiching sediments have an age range of 3059-2704 Ma (Davis et al. 1989, errors are generally  $\pm 2-3$  Ma). The Coutchiching Group was deformed and metamorphosed as part of a dome structure at Rice Bay, and intruded by post-tectonic plutons such as the Bear Pass stock at  $2693 \pm 2$  Ma. Detrital zircon grains in the Seine Group have a uniform age of 2693 Ma. Therefore, both sedimentary groups are quite late in the geologic history of the area but the Seine Group post-dates deposition of the Coutchiching Group and may have been derived from erosion of an active volcanic edifice overlying the rising Rice Bay dome.

The voluminous Quetico turbidites to the south have a detrital zircon age range of 3009-2698 Ma, and were intruded by the late tectonic Blalock Pluton at  $2688 \pm 4$  Ma (Davis et al. submitted). Deposition of the Seine Group may, therefore, have been penecontemporaneous with parts of the Quetico sediments. This is supported by field evidence in the Geraldton area where Devaney and Williams (1989) have demonstrated a transition between alluvial and marine sediments at the northern boundary of the Quetico Subprovince.

Detrital zircons in both the Quetico and Coutchiching sediments have a distinctive

age pattern in which many of the grains cluster near the young end of the age range, and are similar in age to late-tectonic plutons in the adjacent Wabigoon Subprovince. The other grains are generally older than arc-type volcanism in adjacent greenstone belts, but similar in age to rocks found within metaplutonic terrains in the Wabigoon Subprovince and the Winnipeg River Subprovince. There is also petrographic evidence that significant amounts of felsic volcanic material contributed to the provenance of the turbidites. These data indicate that Quetico-type sediments may have been deposited largely from erosion of active volcanos and older sialic crust during a late orogenic event.

The relationship between sedimentation and deformation is clearly evident in the Manitou Lake area, at the southern margin of the Kakagi Lake - Savant Lake volcanic belt. Alluvial sediments are overlain by marine turbidites (Manitou Lake Group, Teal and Walker 1977), which are, in turn, structurally overlain by volcanic rocks (Boyer Lake Group). Detrital zircons in the turbiditic sediments show an age range 3039-2706 Ma. Sediments near the base are intercalated with rhyolites with an age of  $<2699 \pm 3$  Ma. The overlying Boyer Lake group has an older age of  $2722 \pm 5$  Ma and was therefore structurally emplaced over the sediments, possibly by thrusting. The entire sequence was rotated into a vertical position and intruded by the post-tectonic Taylor Lake stock at  $2696 \pm 2$  Ma. Therefore, sedimentation, probable thrusting, regional folding and late magmatism occurred within a time span of, at most,  $3 \pm 4$  Ma and were likely part of a single tectonic event. Also, the presence of out-of-sequence relationships within the supracrustal pile suggests that the turbidites may have been structurally superposed on the lower alluvial sediments.

Almost identical relationships are found within the supracrustal sequence in the Sioux Lookout area, on the northern boundary of the Kakagi Lake - Savant Lake volcanic belt (Davis et al. 1988). This sequence is structurally overlain by the Warclub Group, a belt of turbidites which extends westward along part of the boundary between the Wabigoon and Winnipeg River Subprovinces. The detrital zircon age pattern of turbidite in the Dryden area indicates that much of the sediment was probably derived from the Winnipeg River Subprovince. Deposition is dated at about 2714 - 2706 Ma based on the age of an intercalated rhyolite and age constraints from clastic material and emplacement of the Dryberry batholith. This time span correlates with deformation, late plutonism and gold mineralization at the northern boundary of the Wabigoon Subprovince, as well as with metamorphism in the Winnipeg River Subprovince, and tectonic activity between the two subprovinces (Davis and Smith, submitted).

In summary, deposition of clastic sediments appears to mark the onset of collisional orogeny. Time constraints on this process from north to south across the western Superior Province are the following: 2714-2706 Ma in the northern Wabigoon Subprovince, 2699-2696 Ma in the central Wabigoon, 2698-2688 Ma in the Quetico Subprovince, and 2689-2684 Ma in the Shebandowan Subprovince (Corfu and Stott 1986). This process was apparently diachronous across the Superior Province and may have been due to progressive southward accretion of arc and micro-continental fragments.

- Corfu, F., and Stott, G.M. 1986. U-Pb ages for late magmatism and regional deformation in the Shebandowan Belt, Superior Province, Canada. *Can. Jour. Earth Sci.*, v. 23, p. 1075-1082.
- Davis, D.W., Pezzutto, F., and Ojakangas, R.W. The age and provenance of metasedimentary rocks in the Quetico Subprovince, Ontario, from single zircon analyses: implications for Archean sedimentation and tectonics in the Superior Province. submitted to *Earth Planet. Sci. Lett.*
- Davis, D.W., Poulsen, K.H., and Kamo, S.L. 1989. New insights into Archean crustal development from geochronology in the Rainy Lake area, Superior Province, Canada. *Jour. Geol.*, v. 97, p. 379-398.
- Davis, D.W., and Smith, P.M. Archean gold mineralization in the Wabigoon Subprovince, a product of crustal accretion: evidence from U-Pb geochronology in the Lake of the Woods area, Superior Province, Canada. submitted to *Jour. Geol.*
- Davis, D.W., Sutcliffe, R.H., and Trowell, N.F. 1988. Geochronological constraints on the tectonic evolution of a late Archean greenstone belt, Wabigoon Subprovince, northwest Ontario, Canada. *Precamb. Res.*, v. 39, p. 171-191.
- Devaney, J.R., and Williams, H.R. 1989. Evolution of an Archean subprovince boundary: a sedimentological and structural study of part of the Wabigoon - Quetico boundary in northern Ontario. *Can. Jour. Earth Sci.*, v. 26, p. 1013-1026.
- Lawson, A.C. 1887, Geology of the Rainy Lake region, with remarks on the classification of the crystalline rocks west of Lake Superior. *Am. Jour. Sci.*, v. 33, p. 473-480.
- Lawson, A.C. 1913, The Archean geology of Rainy Lake re-studied. *Can. Geol. Survey Mem.* 40, 111 p.
- Ojakangas, R.W. 1985. Review of Archean clastic sedimentation, Canadian Shield: major felsic volcanic contributions to turbidite and alluvial fan-fluvial facies associations. in Ayres, L.D. et al., eds., *Evolution of Archean supracrustal sequences*, Geol. Assoc. Canada Spec. Paper 28, p. 23-47.
- Teal, P.R., and Walker, R.G. 1977. Stratigraphy and sedimentology of the Archean Manitou Group, northwestern Ontario. *Geol. Survey Canada, Paper 77-1A*, p. 181-184.

PALEOMAGNETISM OF KEWEENAWAN AGE BASALTS OF THE CHENGWATANA  
VOLCANIC GROUP IN THE ST. CROIX FALLS AND FREDRICK-MILTOWN  
AREA OF POLK COUNTY, WISCONSIN

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Extensive paleomagnetic studies have been made in the Precambrian Keweenawan rocks near the shores of Lake Superior. Over 60 individual paleomagnetic poles have been obtained from these rocks (Halls and Pesonen, 1982). Exposures of Keweenawan age basalts in Polk County (northwestern Wisconsin) give an opportunity to study Lake Superior Keweenawan rocks in their southernmost exposure.

130 oriented cores from 18 sites in the St. Croix Falls and Fredrick-Miltown area of Polk County, Wisconsin were collected and measured for magnetic characteristics. A.F. demagnetization and remanence acquisition studies indicate that the remnant magnetization is carried by magnetite and in some exposures, hematite. Most samples showed a single component of magnetization with Fisher average magnetic directions split into two groups; a normally magnetized, or north seeking direction and a "reverse" direction (Table 1). The normal group gave a magnetic direction and pole position close to the mean values for the middle Keweenawan Portage Lake Volcanic Group given in Halls and Pesonen, 1982, when corrected for geologic dip using lava flow tops. The reverse group showed a large (60 degrees in declination) asymmetry, possibly caused by magnetic overprinting from adjacent normal magnetized basalt flows.

Susceptibility measurements showed a great deal of variation on a within site and a between site basis. Mean susceptibility from all sites was  $2892 \times 10^{-6}$  c.g.s. units, and standard deviation was  $2686 \times 10^{-6}$  c.g.s. units. The low value for a site was  $31 \times 10^{-6}$  c.g.s. units and the high was  $9592 \times 10^{-6}$  c.g.s. units.

TABLE 1

PALEOMAGNETIC PARAMETERS FOR KEWEENAWAN AGE BASALTS OF POLK COUNTY, WISCONSIN\*

| DIRECTION |       | K    | A95  | V.G.P. |         | POL |
|-----------|-------|------|------|--------|---------|-----|
| INC.      | DEC.  |      |      | LAT.   | LONG.   |     |
| 47.2      | 288.4 | 17.7 | 14.8 | 29.7 N | 183.0 E | N   |
| -61.0     | 175.0 | 66.4 | 15.2 | 85.1 S | 316.0 E | R   |
| ** 34.9   | 288.6 | 1332 | 2.5  | 26.5 N | 181.2 E | N   |

Symbols; K - precision parameter; A95 - radius of confidence; V.G.P. - virtual geographic pole position; POL - polarity; N - normal, north seeking magnetization; R - reverse, south seeking magnetization.

\* Corrected for geologic dip based on a flow-top average measurement of N 23W, 21W. Mean site latitude = 45.427N, longitude = 92.611W.

\*\*Portage Lake Volcanic Group mean value.

#### REFERENCE

Halls, H.C., and Pesonen, L.J., 1982, Paleomagnetism of Keweenawan rocks: Geological Society of America Memoir 156, pp. 173-200.

GEOLOGY AND MINERALIZATION IN THE DUNKA ROAD  
COPPER-NICKEL MINERAL DEPOSIT  
ST. LOUIS COUNTY, MINNESOTA

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The Dunka Road Cu-Ni deposit is located within the Partridge River Intrusion (T. 60 W., R. 13 W.) which is part of the Duluth Complex, and is approximately 1.1 b.y. (Keweenawan) in age (Figure 1). Relogging of 46 drill holes at the Dunka Road Cu-Ni deposit identified four major lithologic units and several internal ultramafic subunits that can be correlated over two miles. The ultramafic subunits (layers of picrite to peridotite), exhibit relative uniform thicknesses and are present at the same relative position within the major lithologic units. The major lithologic units are the same as delineated by Severson and Hauck (1990), and upward from the basal contact are: Unit I, a fine- to coarse-grained sulfide-bearing troctolite to pyroxene troctolite (450 ft. thick) with associated ultramafic layers I(a), I(b), and I(c); Unit II, a medium- to coarse-grained troctolite to pyroxene troctolite (200 ft. thick) with a basal ultramafic layer II(a); Unit III, a fine-grained, mottled textured troctolitic anorthosite to anorthositic troctolite (150 ft. thick) with one minor ultramafic layer III(a); and Unit IV, a coarse-grained troctolite/pyroxene troctolite to anorthositic troctolite with associated ultramafic layers IV(a) and IV(b) (Figure 2).

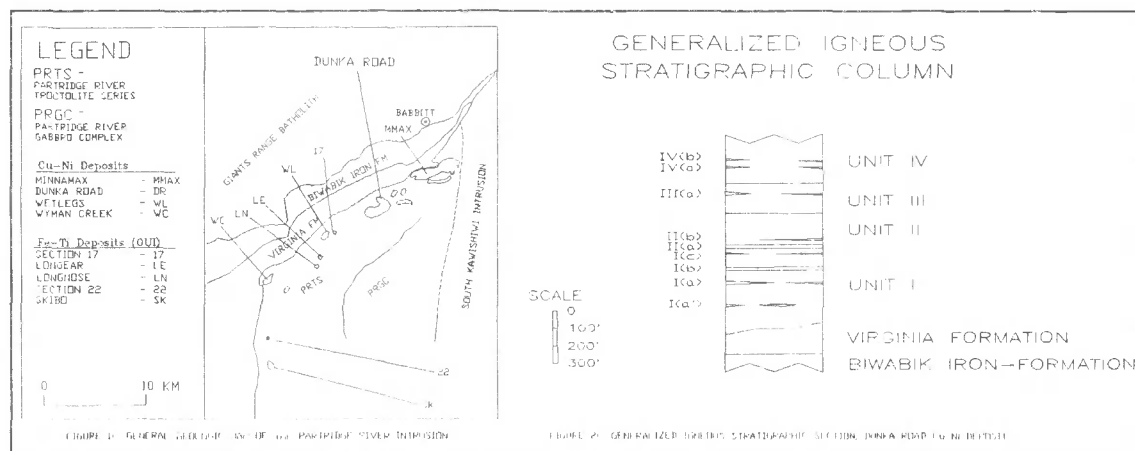
Most sulfide mineralization occurs within Unit I. Within Unit I the sulfide mineralization is both widespread but variable in modal percentage (rare to 5%), continuity and thickness (few inches to tens of feet). Sulfide mineralization is generally related with proximity to: hornfels inclusions, basal contact with the footwall Virginia Formation, and some of the internal ultramafic layers within Unit I. Primary sulfide mineralization includes pyrrhotite, chalcopyrite and pentlandite. Minor amounts of cubanite, bornite, talnakhite and mackinawite/valleriite have also been identified in preliminary petrographic observations. Precious metal mineralization (Pd+Pt+Au) is associated with subtle fracturing and alteration of the host rocks. The alteration assemblage is chlorite, bleached plagioclase, serpentine and urallite. Secondary sulfide mineralization occurring as trace amounts of bornite, is present in these fractured and altered zones.

Pd+Pt values range from 100 to >2400 ppb over 10 foot intervals. These intervals can occur independently as 10 to 50 foot zones, or as part of a larger correlatable occurrence/horizon. Two mineralized subareas were investigated

within the Dunka Road deposit and are: 1) an area which is perforal to a highly anomalous Pd occurrence (reported by Morton and Hauck, 1987; 1989) herein termed the "southwest area", and 2) the "northeast area" which contains several drill holes that have near-surface intercepts of  $> 1\%$  Cu. There are four somewhat large mineralized occurrences within the study area that carry  $>300$  ppb combined total Pt+Pd+Au. These mineralized zones appear to be stratigraphically controlled by ultramafic subunits within Unit I. Three of the four correlatable zones are found within the southwest area, and range from 40 to 130 feet thick. High Pd values within these zones range from 10 to 20 feet thick with values of 800 to 1650 ppb Pd. In the northeast area, the fourth mineralized zone appears continuously throughout Unit I. This zone ranges from 120 to 300 feet thick. High Pd values within this zone range from 10 to 40 feet thick with values of 800 to 1500 ppb Pd. Many 5 to 30 foot intersections of  $>1$  ppm Pd+Pt+Au occur throughout the mineral deposit.

#### References:

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

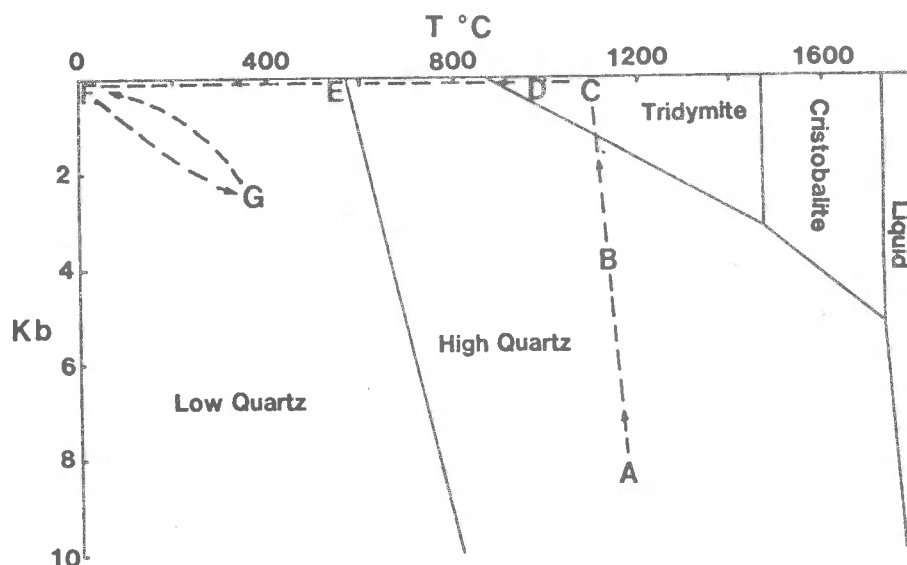


## TRIDYMITE, OTHER $\text{SiO}_2$ MINERALS AND THE P/T TRAJECTORY OF KEWEENAWAN LAVAS, MINNESOTA

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Four  $\text{SiO}_2$  minerals (cristobalite, tridymite, beta and alpha quartz) have crystallized at one stage or another in rhyolites of the North Shore Volcanic Group. Whereas cristobalite is known only from occasional, hemispherical quartz paramorphs in vesicles (metastable, pneumatolytic), and perhaps in spherulites, tridymite was the silica mineral stable during flow and crystallization of most rhyolites. This is indicated particularly by the near ubiquity of flow structure formed by quartz paramorphs after platy tridymite. (Many of the lavas had previously started to crystallize beta quartz - now present as phenocrysts - at higher P in deeper chambers within the crust.) Aphyric rhyolites ponded and also crystallized tridymite (+ feldspar) at the surface, without flow structure. On cooling past 870 degrees C, late-crystallizing domains crystallized beta-quartz (+ fsp) to the solidus. Below 573 degrees, the beta quartz inverted to alpha quartz, and some hydrothermal/pneumatolytic quartz was probably deposited in openings. Upon later burial to several kilometers' depth and re-warming (hydrothermal/burial "metamorphism"), the metastable tridymite plates inverted to alpha quartz. In porphyritic rhyolites, this nucleated on the quartz phenocrysts to give a remarkable poikilitic ("snowflake") texture.

The widespread primary crystallization of tridymite is unusual, though noted in certain rhyolites around the world, and implies anomalously high temperatures of eruption.



## Transposition structures in deformed rock, with examples from the Appalachians and Upper Michigan

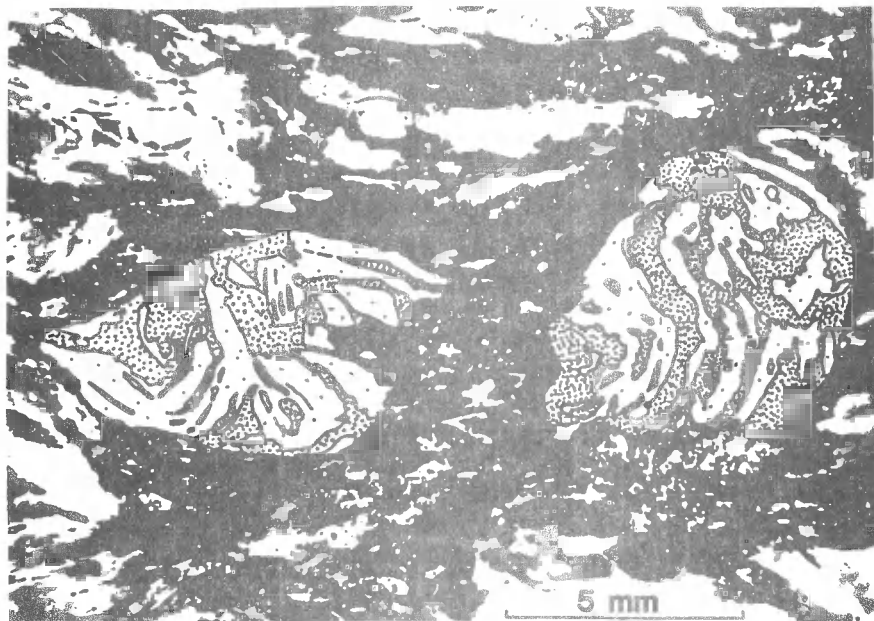
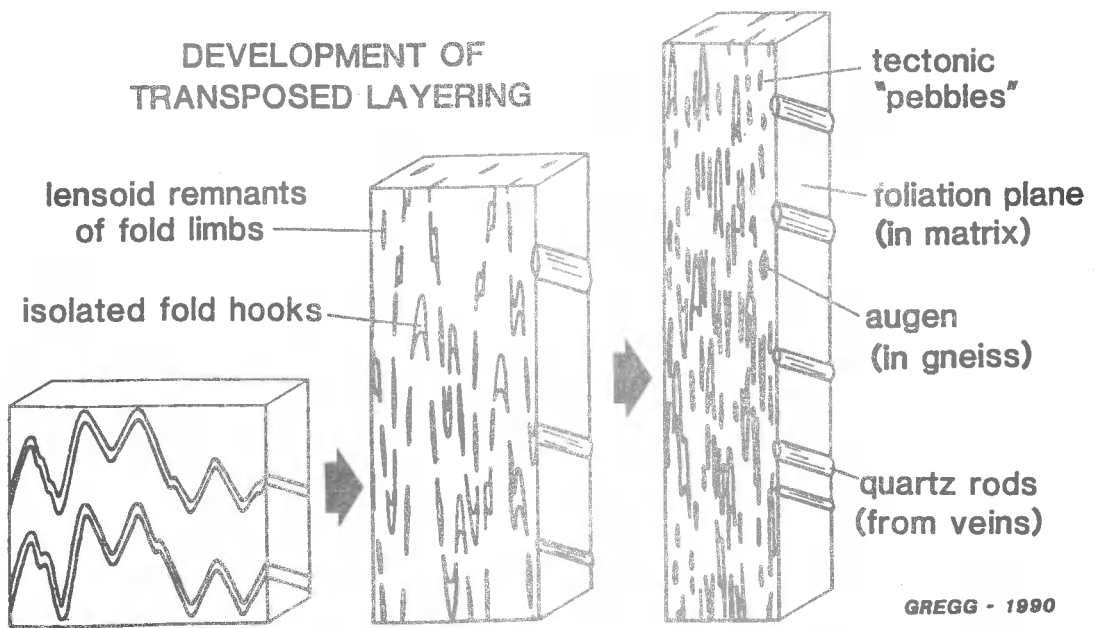
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The term 'transposition' has come into wide usage in published descriptions of deformed rocks. Unfortunately there has been little consistency in its application, and the term has been inappropriately applied to a wide variety of structures, including slaty cleavage (Burger 1982), crenulation cleavage (Rickard 1961) and schistosity (Whitten 1966), in situations where these foliations either render a pre-existing foliation obscure, or when they form domain boundaries between rotated segments of an earlier foliation. This broad usage of the term to indicate any sort of realignment of a layering has resulted in much confusion, and many rocks that are truly transposed have remained unrecognized as such to this day. This confusion stems largely from a mistranslation of Sanders (1911) work by Knopf (1931) in which illustrations of transposition were perhaps inadvertently switched with crenulation cleavage.

As Sander pointed out, transposition (Umfaltung) is a mechanical process that produces lenticular elements from a previous layering. The elements are produced by isoclinal folding of competent layers, followed by boudinage of the layers along the fold axial surface in a direction normal to the fold axes. A new foliation need not be present in the transposed layer itself and as Sander stated "the original S layers are still present, but are only misoriented by small particulate displacements". Sander never used the misnomer "Umfaltungsclivage" as quoted by others (Knopf 1931, p. 16), and was careful to point out that "cases of true cleavage can be defined when a new S cuts an older one" whereas in transposition the early S surface "is indeed transposed but not however cut by a new S".

Studies of transposed layering from the Northern Appalachians and Upper Michigan show that transposition usually develops only in rocks that have a mechanical anisotropy in the internal layering. Although an entire rock unit is sometimes described as transposed, it is actually only the competent layers within the unit that show this type of deformation. The matrix around the competent layers may instead be characterized by a high strain foliation such as schistosity or pinstripe layering.

Transposed layering usually is recognized by the presence of features such as rootless isoclinal fold hooks and lensoid remnants of fold limbs (Williams 1967). These structures may represent the dismembered portions of bedding, although thick secondary layers may also be transposed. The transposition of quartz veins in pelitic rocks is extremely common, resulting in white quartz lenses and in quartz-rich rod structures that parallel the axes of



"Whorl" structures in transposed "Springfield Conglomerate" from Central Vermont. Specimen, from type locality, is a chloritized, sulfide-rich mafic rock.

the earlier isoclinal folds. Some types of 'button' structure (Roper 1972) observed in phyllites may also represent interfolial transposed segments. In Archean rocks transposition is frequently responsible for the development of augen structure, for example in the Watersmeet gneisses in Upper Michigan and in numerous examples from the Green Mountains and the Adirondacks.

When flattening strains are extremely high, isoclinal fold hooks may be difficult to observe, and the rock may take on the appearance of a pseudo-conglomerate (Ramsay 1956). A number of cases exist where transposed rocks in regionally significant high strain zones have been misidentified as sedimentary units, for example the Paleozoic Dry Hill Conglomerate and Springfield Conglomerate units in south-central Vermont.

In severely transposed rocks isolated fold hooks may form whorl-structures that show evidence of rotations in the plane of foliation. These structures indicate high vorticity in transposed zones which seems to be little evidenced in less transposed fabrics. The whorl structures eventually suffer severe delamination and internal disruption as strain progresses.

#### REFERENCES

- Burger, R. H., 1982, Solution cleavage and bedding transposition": in Bayly, B. M., Borradaile, G. J., and Powell, C. McA., eds., Atlas of Deformational and Metamorphic Rock Fabrics, Springer Verlag, p. 330-331.
- Knopf, E. B., 1931, Retrogressive metamorphism and phyllonitization: Amer. Jour. Sci., v.21, p. 1-27.
- Ramsay, J. G, 1956, The supposed Moinan basal conglomerate at Glen Strathfarrar, Inverness-shire: Geol. Mag., v. 93, p. 32-40.
- Rickard, M. J., 1961, A note on cleavages in crenulated rock: Geol. Mag., v.98, p. 324-332.
- Roper, P. J., 1972, Structural significance of "button" and "fish scale" texture in phyllonitic schist of the Brevard Zone, Northwestern South Carolina: Geol. Soc. Amer. Bull., v. 83, p. 853-860.
- Sander, B., 1911, Über Zusammenhänge zwischen Teilbewegung und Gefüge in Gesteinen: Tscher. Min. Petr. Mitt., v. 38, p. 281-317.
- Whitten, E. H. T., 1966, Structural Geology of Folded Rocks, Chicago, Rand McNally, 663 p.
- Williams, P. F., 1967, Structural Analysis of the Little Broken Hill area of New South Wales: Jour. Geol. Soc. Australia, v. 14, p. 317-332.

## GEOLOGY OF WRIGHT COUNTY USING WELL LOG DATA

by

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Wright County well logs were used to map bedrock types, bedrock elevations, possible faults, including a previously unmapped major fault trending southwest-northeast through Wright County and a possible explanation for the positioning of the Mississippi River Channel. Glacial sediments were also mapped using well logs to give a more precise placement of the St. Croix Moraine, and a repositioning of the mapped path of the Grantsburg Sublobe of the Des Moines ice sheet.

Three thousand Minnesota Department of Health well logs were used out of a total of 5000 available for Wright County. The remaining 2000 logs were rejected for various reasons including incomplete or inaccurate location and strata files. Each log had the following format: location (Township-Range-Section), strata, and strata thickness. Sediments and bedrock types were cataloged into standardized formations, e.g. sandy-clay and clay-sand were both classified as clay-sand. Standardization was necessary because percent composition of strata was rarely given. Strata color was also standardized so that, for example, light-green, green, and dark green were all classed as green.

It should be noted that well drillers are not geologists; however, they do know the differences between sand and shale, clay and gravel, etc., and differences in color.

Township-range locations were transformed into rectilinear coordinates with a Z-attribute. For numerical data with three-dimensional characteristics a map file was generated using the program "SURFER" (Golden Graphics Software, Inc.). The file was then converted into a Geographic Information System attribute file compatible with "EPPL-7" (a GIS program developed by the Land Management Information Center, Minnesota State Planning Agency). Non-numerical attribute data was mapped using a Thiessen Polygon Method developed by Dr. Charles L. Nelson, Earth Sciences Department, St. Cloud State University.

Bedrock maps show a curved trend from just east of the city of Cokato to southwest of Monticello. Along this fault are several series of lakes and other topographic features which seem to indicate bedrock control. Displacement along the fault is unknown. Bedrock elevations are highest in the north-northwestern margin of the county. An irregular bedrock ridge extends to the east-southeast. The ridge is breeched by several swales. On the southern margin of the ridge are several semi-enclosed depressions. A wide low-relief buried valley trends south from the center of the county.

At an elevation of 900 feet above sea level Wright County is covered by unconsolidated sediments with an isolated sandstone deposit near the Mississippi River near the village of Otsego. At 850 feet isolated pockets of

sandstone and red granites occur along the river. Patches of shale cover both unconsolidated sediments and sandstone in a northwest to southeastern trend. Beneath unconsolidated sediments in the northwestern corner at 800 feet an area of about 10 square miles of sandstone exists. A nearly equal area of sandstone also exists on the far eastern side of the county. A larger region of shales occur in the center of the county. At the 750 foot elevation sandstone underlies the 800 foot level shales. Cretaceous shales covers the southwestern quarter. An arcuate band of sandstones cuts through the eastern part of the county. At 700 feet above sea level grey granite appears in the west central part of the county. Along the river red granites are interspersed with sandstones and shales. Shales cover the central section with sandstones and unconsolidated sediments occurring in the southeast. A five mile wide band of sandstone surrounding red granites parallels the river at 650 feet. The southeast quarter is also sandstone. Shales and unconsolidated sediments separate the two sandstone bodies. Granites occupy the western one-third of the county.

There are four bedrock valleys, trending south-southwest to north-northeast near the cities of Annandale, Clearwater, Silver Creek, and Monticello. The Mississippi River appears to be constrained at present by a series of small buried red granite bedrock highs on the south side of the river. The river was possibly kept to the north of the bedrock highs by Grantsburg Sublobe meltwater and sediments, flowing through the aforementioned valleys. The Clearwater channel is apparent even in the glacial sediments at the surface. It is the widest of the bedrock channels with a maximum width of one and a half miles. Several narrower and shorter but deeper channels extend northward to the Mississippi River, past the towns of Maple Lake, Silver Creek and Hasty.

Several long surface channels eroded into glacial sediments trend northward through morainic hills. Some of these channels are superimposed above buried bedrock channels. One channel may be a glacial tunnel valley. The slope of the floor is not consistent, a drainage divide exists midway along the valley, there are also several enclosed depressions. Water flowing through a glacial tunnel is capable of undulating up and down slopes.

The surface of the northern half of Wright County is St. Croix end moraine. The hills are composed of thick deposits of very red clay. They trend from the northwest to the southeast. Deposition thickness can exceed 200 feet. The end moraine is located on the southern flank of the bedrock high. The central part of the county consists of reworked preexisting glacial sediments and Des Moines Lobe tills. An eight mile long esker meanders across Des Moines ground moraine in the east-central part of the county from Pelican Lake southward to the Crow River valley. Des Moines tills cover the southern portion of the county. There is little or no correlation between the deposition of Des Moines tills and bedrock topography. There is some correlation between Des Moines outwash and bedrock topography.

From high resolution mapping of bedrock elevations and detailed analysis of glacial sediments of the St. Croix End Moraine, the path of the Grantsburg Sublobe of the Des Moines ice sheet is farther to the east than mapped by earlier investigators.

# STRUCTURAL ANALYSIS OF ARCHEAN METASEDIMENTARY ROCKS IN THE VICINITY OF THE MINERAL HILL GOLD MINE, JARDINE, MONTANA

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Jardine is located along the western margin of the Beartooth Mountains in southwestern Montana. Placer gold was discovered in the Jardine region in 1866, and by the mid 1880's, Precambrian iron formation-hosted lode gold was being mined on Mineral Hill. In 1984, the Jardine Joint Venture was formed between American Copper and Nickel Company (ACNC) and Homestake Mining Company, with ACNC acting as the operating partner. Renewed surface and underground exploration by ACNC has shown Mineral Hill to have a probable ore reserve of 1.0 million tons at a grade of 0.3 ounces of gold per ton.

The bedrock geology of the Jardine area consists predominantly of Archean metasedimentary rocks which were intruded by granitic stocks and minor mafic dikes and sills. Greywacke and mudstone sequences, which were deposited by turbidity currents, have been regionally metamorphosed to quartz-biotite schist and biotite schist, respectively. The original thickness of the sedimentary pile is unknown, and a diamond drill hole on Mineral Hill, which was drilled to a depth of over 2000 ft., failed to intercept the basement to these sediments. The thickness of the sedimentary pile has probably been exaggerated by tectonic thickening during isoclinal, recumbent folding. The monotonous nature of this thick pile of metasedimentary rocks is interrupted by a silicate facies iron formation which acts as the only stratigraphic marker horizon in the Jardine region. It is this iron formation and proximal schists which host the gold mineralization.

Calculations from microprobe analyses of coexisting biotite and staurolite in an aluminum silicate-rich sample, show that peak metamorphism occurred at a pressure and temperature of approximately 2.9 kb and 560° C, respectively.

Evidence for three generations of Precambrian folding has been recognized in the Archean metasedimentary rocks of the Jardine region. During the earliest fold phase ( $F_1$ ), isoclinal, recumbent folds were formed. A foliation plane,  $S_1$ , defined by the growth and preferred orientation of micaceous minerals, was created during the  $F_1$  fold event and is observable throughout all rock types in the region. The orientation of this schistosity is along or nearly parallel to the original compositionally- and texturally-defined bedding planes.  $S_1$  surfaces were subsequently crenulated during the second ( $F_2$ ) and third ( $F_3$ ) fold events.  $F_2$  and  $F_3$  fold axial surfaces are upright and at a high angle to  $F_1$  fold axial surfaces and to each other.  $S_2$  and  $S_3$

foliations are axial planar crenulation cleavages of  $S_1$ . This zonal crenulation cleavage (Marshak and Mitra, 1988) is defined by the axial planar alignment of microfold hinges (symmetric zonal crenulation cleavage) and/or domains of reoriented micas (asymmetric zonal crenulation cleavage) and is not the result of recrystallization of micaceous minerals in the microfold hinges. Linear structures are found predominantly in biotite schist because of its rheology and the nature of the deformations.  $L_2$  and  $L_3$  lineations are the intersection of  $S_2$  and  $S_3$  axial planar crenulation cleavage surfaces in the  $S_1$  foliation surface.  $F_2$  fold axes were the only minor fold lineations which were directly measurable from outcrop.

The dominant fold interference pattern created by fold superposition is a Ramsay (1962), Type 1, dome and basin pattern. The interference of  $F_2$  and  $F_3$  folds are responsible for this pattern. The structural history (see diagram below) involves early isoclinal, recumbent  $F_1$  folding (Figure 1A), with later refolding by  $F_2$  folds, with  $F_2$  axial surfaces at a high angle to  $F_1$  axial surfaces (Figure 1B).  $F_3$  fold axial surfaces are at high angles to  $F_1$  and  $F_2$  fold axial surfaces (Figure 1C) and refold both sets of earlier folds. A firm understanding of this fold form is important for future regional exploration, since it has been shown that the highest grade of gold mineralization occurs in the domes of the folded iron formation (John Cuthill, personal communication, 1989).

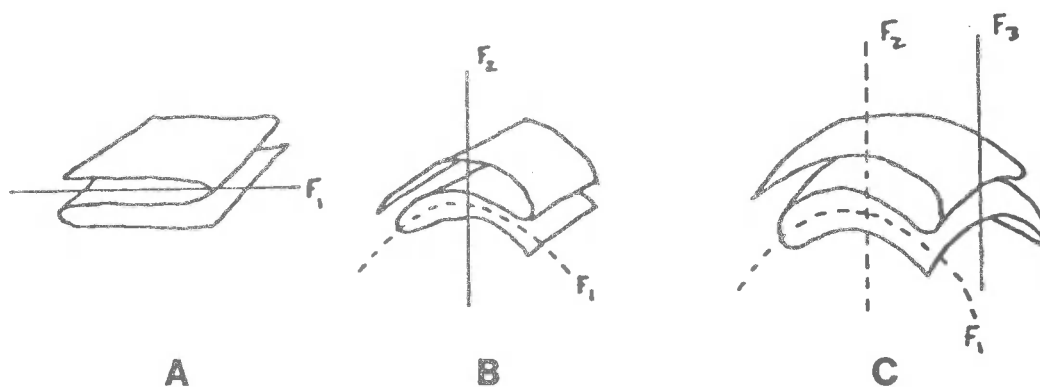


FIGURE 1

### References

- Marshak, S., and Mitra, G., 1988, Basic methods of structural geology: New Jersey, Prentice-Hall, Inc., 445 p.
- Ramsay, J. G., 1962, Interference patterns produced by the superposition of folds of similar type: *Journal of Geology*, v. 70, P. 466-481.

# REVERSE ZONATION IN THE LESTER RIVER SILL, DULUTH, MINNESOTA, AND EVIDENCE FOR POLYBARIC FRACTIONATION

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The Lester River Sill intrudes, and is roughly concordant with, the extrusive flows that constitute the North Shore Volcanic Group (NSVG) of Keweenawan Age (1.1Ga). The sill is one of three large sills found in the city of Duluth, Minnesota, the others being the Endion and Northland sills, first studied by (1). Since then, the 425 m thick Endion Sill has been the most intensely studied (2, 3, 4), and the smaller Northland Sill has also been investigated (5).

The most extensive outcrop of the Lester River Sill occurs in Duluth, along the shore of Lake Superior, beginning just north of the Lester River and continuing approximately 1.8 km in Kitchi-Gammi Park. It can be followed inland along a strike of approximately N18°E as a well defined ridge extending over 25 km. The sill dips ~20° to the southeast, indicating a thickness of ~280 m. Outcrop along the shore is excellent, and nearly continuous, providing a good cross-section.

Chemical analysis of 36 samples from the sill was undertaken utilizing instrumental neutron activation analysis (INAA) and electron microprobe analysis of fused glass beads, yielding data for 34 elements. This particular sill exhibits a "reverse" zonation, with the most primitive diabase (i.e. diabase with the highest  $mg$  [molar  $MgO/(MgO+FeO)$ ] and the lowest abundance of incompatible elements and  $SiO_2$ ) occurring in the central regions. The lower half (140 m stratigraphically) is medium-grained, intergranular diabase. The upper portion of the sill is more varied. Most of it is an ophitic diabase, with individual pyroxene grains up to 1 cm across. Near the top of the sill, stringers of red material become more abundant until, at the topmost part, the rock is a granophyre.

In general, crystallization from the margins in large sills results in the most evolved material being located in the medial portion. An example is the Palisades Sill of New Jersey (e.g. 6). In the Palisades Sill, the silica content ranges from about 52% at the margins to 60% in the most evolved rocks, and the incompatible trace elements show great enrichment (Fig 1a). Although the thickness of the Lester River Sill is less than that of the Palisades Sill, it is large enough to expect extensive fractionation in a slowly cooling environment. The chemical trends across the sill (Fig. 1b) are opposite in sense to those trends observed in the "normal" Palisades Sill, with the most

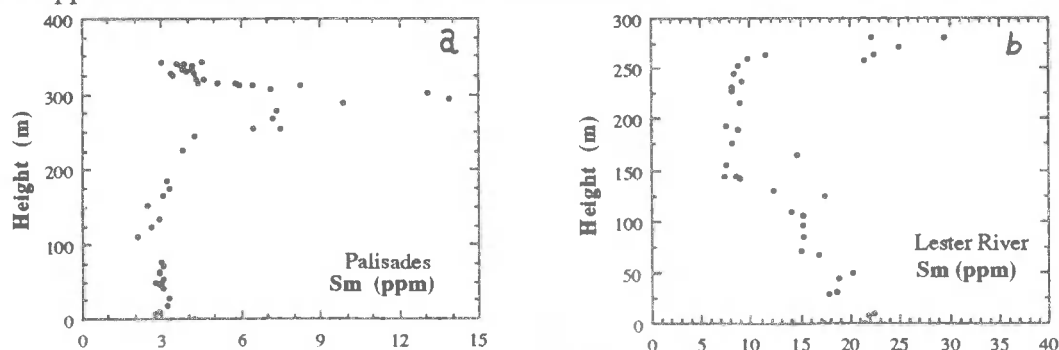


Figure 1. Samarium variations across the Palisades and Lester River Sills.

primitive material in the medial portions of the Lester River Sill. Although this facies represents the primitive part of the Lester River Sill, it is considerably more evolved ( $mg \approx 0.45$ ) than the primitive olivine tholeiites of the NSVG ( $mg \approx 0.65$ ; [7]), or even the majority of diabases from the rest of the North Shore ( $mg \approx 0.55$ ).

The "reverse" zoning profile seen in the Lester River Sill makes it unique among the hypabyssal rocks of the North Shore. Indeed, such profiles are rare among sills in general. In Antarctica, the Lake Vanda Sill and Emmanuel Sheet show similar trends (8), although these are not as pronounced as in the Lester River Sill. In the Antarctic bodies, few of the elemental concentrations vary by as much as a factor of 2 across the sills (even in the incompatible elements), whereas in the Lester River Sill the variations are up to factors of 3.

A likely process that could have produced the pattern seen in the Lester River Sill is some form of multiple intrusion. Multiple intrusion is the preferred model for the emplacement of the 425 m thick Endion Sill to the south of the Lester River Sill (3, 4).

The Lester River Sill is located between an andesite and a rhyolite of the NSVG. The temperatures of the intruding material would have been well above the melting point of the rhyolite, and it is apparent from the presence of stringers and blebs of felsic material in the upper portions of the sill, that extensive assimilation of the rhyolite took place there. In the profile of Fig. 1b, this assimilation is reflected in the chemical trend at the top, which describes a mixing line between the primitive diabase and the rhyolitic host rock. In the inland areas of the Lester River Sill, where rhyolite was not in contact with the diabase, there is no "red rock" zone, and no discernible mixing features. It is presumed that the most primitive diabase of the sill was intruded first, since it is this material that contains the blebs and stringers of felsic rock indicating assimilation. Further intrusion of more evolved magmas below those already present could produce the profile observed.

Mass-balance calculations were undertaken in an attempt to model the generation of the primitive diabase in the Lester River Sill. A parent of mean primitive olivine tholeiite composition from the NSVG (7) was chosen for mass-balance calculations. From this parental composition, successive increments of fractionating assemblages were subtracted (each increment consisted of 1 wt% solids). These assemblages consisted of ol + plag  $\pm$  cpx, which form the majority of early solids produced during the crystallization of basaltic magmas. Mineral compositions are calculated separately for each increment.

In order to successfully obtain compositions similar to the more primitive diabase in the Lester River Sill, the modelling indicated that the first stage of the fractionation must consist of the 3-phase (3 $\phi$ ) assemblage ol + plag + cpx, followed by a stage of ol + plag, and a third stage with 3 phases again (Fig. 2). The implication of the calculations is that at least two (and possibly more) separate magma chambers at differing crustal levels are required to produce the first Lester River Sill magma from the primitive olivine tholeiite. This results from the strong effect of pressure on the clinopyroxene stability field for basaltic liquids, which shrinks with decreasing pressure. Therefore, a magma which crystallizes ol + plag + cpx at depth and then rises to a higher, lower pressure position in the crust could be expected to crystallize only ol + plag for a time at the new location due to this shrinkage of the cpx stability field. At some later time, cpx would then reappear as a crystallizing phase. Magma rising to a still higher level would again result in only ol + plag crystallizing. Polybaric fractionation such as this has been used to explain trends observed in continental flood basalts (e.g. 9), and has also been proposed for the origin of the compositions

seen in some of the Lake Superior volcanics (10).

Additional evidence for polybaric fractionation can be found using a pseudo-liquidus phase diagram (Fig. 3). In this diagram, the primitive olivine tholeiites of the NSVG plot in a region consistent with a magma that is multiply saturated at an elevated pressure (~10 kb). The most evolved material of the Lester River Sill is seen to be consistent with multiple saturation at a pressure considerably lower (i.e. ~1 atm). The primitive part of the sill is intermediate, suggesting a region between the two (roughly 3 kb?).

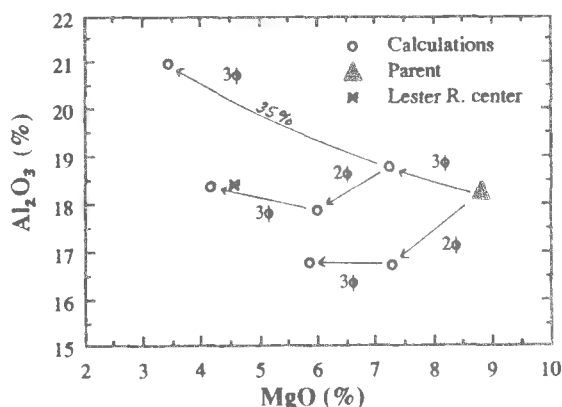


Figure 2. Mass-balance results for the Lester River Sill. Each stage is ~25% crystallization.

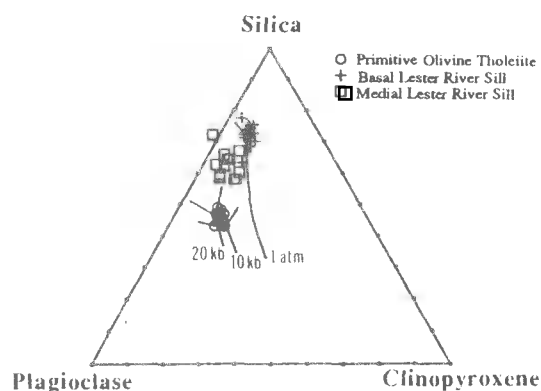


Figure 3. Pseudo-liquidus phase diagram for the Lester R. Sill and primitive ol. tholeiites.

Intuitively, it is not hard to imagine several magma chambers forming at different levels in a rifting environment where fracturing is pervasive. Evidence exists for a high level chamber below the Krafla volcanic center in Iceland, deduced from studies of caldera inflation rates (11, 12). This chamber is presumed to be an upper crustal chamber filled from another one below, leading to inflation and uplift of the caldera floor. After a period of time, the magma is injected into the surrounding area, forming numerous dikes. This process is analogous to that suggested above for the formation of the Lester River Sill. There is additional evidence that lateral transport of magma along the rift over moderately large distances (~70 km) occurs in Iceland (13). If a similar process occurred in the Midcontinent Rift, it may begin to explain the striking similarity of compositions observed among the other hypabyssal rocks found all along the north shore of Lake Superior.

## References

- (1) Schwartz, G.M. and Sandberg, A.E. (1940) *Geol. Soc. America Bull.*, **51**, 1135-1172.
- (2) Ernst, W.G. (1960) *J. Petrol.*, **1**, 286-303.
- (3) Oestrike, R.W., Jr. (1983) Unpub. M.S. thesis, Univ. of Illinois, Urbana-Champaign, 141p.
- (4) Gardner, J.E. (1987) Unpub. M.A. thesis, Washington University, St. Louis, 359 p.
- (5) Seifert, K.E. (1985) *Geol. Soc. America Abstracts with Prog.*, **17**, 325-326.
- (6) Shirley, D.N. (1987) *J. Petrol.*, **28**, 835-865.
- (7) Brannon, J.C. (1984) Unpub. Ph.D. dissertation, Washington University, St. Louis, 312 p.
- (8) Gunn, B.M. (1966) *Geochim. Cosmochim. Acta*, **30**, 881-920.
- (9) Cox, K.G. (1980) *J. Petrol.*, **21**, 629-650.
- (10) Klewin, K.W. (1989) *J. Geol.*, **97**, 65-76.
- (11) Johnsen, G.V., Björnsson, A., and Sigurdsson, S. (1980) *J. Geophysics*, **47**, 132-140.
- (12) Sigurdsson, H. (1987) in *Mafic dyke swarms: Geol. Assoc. Canada Spec. Paper 34*, 55-64.
- (13) Sigurdsson, H., and Sparks, R.S.J. (1978) *Nature*, **274**, 126-130.

**STATE OF MINNESOTA  
DRILL CORE LIBRARY**

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Division of Minerals

**ABSTRACT**

The State of Minnesota Drill Core Library is located in the city of Hibbing, a 90 minute drive northwest of Duluth. The library hours are 8:00 am to 4:30 pm daily; Minerals Division staff are available during this time to discuss Division projects or subjects related to Minnesota's mineral potential. Geologists are welcome to examine and/or sample drill core; reservations are encouraged.

Drill core and cuttings resulting from iron, base and precious metal exploration in Minnesota are currently stored in two buildings. In anticipation of further drill core acquisitions, a third building with a capacity of 630,000 feet was constructed. With the additional storage, the Drill Core Library capacity has been expanded to over 2 million feet. Currently, the total amount of drill core and cuttings available exceeds 1.5 million feet, and additional drill holes are added monthly. Also as a result of the new expansion, the library examination table space has increased from 55 to 166 linear feet.

Drill Core is available from 57 of the 87 Minnesota counties, including all of the counties in the Canadian Shield Terrane of northern Minnesota. These cores are collected through the state's exploratory boring law, which requires companies to submit their drill core to the state at the termination of their state or private lease. An index for the Drill Core Library is available in both printed and computerized formats and is sorted by geographic location, as are the corresponding paper files.

Other related information available at the Division of Minerals office includes: lithologic logs for many of the drill holes, geochemical analyses and assays, geophysical studies, and an excellent thin section and polished thin section collection (microscopes can be reserved if needed).

For further information or reservations, contact:

Mineral Resources Geologist  
DNR - Minerals Division  
P.O. Box 567  
Hibbing, MN 55746

Phone: (218) 262-6767

## THE SIGNIFICANCE OF REGIONAL-SCALE LEFT-LATERAL FAULTING IN DEVELOPMENT OF THE VERMILION GREENSTONE BELT IN MINNESOTA

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Northeast-trending longitudinal faults were recognized by the earliest mappers in the Vermilion greenstone belt (VGB), but until recently their role in the tectonic evolution of the belt was unclear. Even in the best-exposed areas of northeastern Minnesota, longitudinal faults are rarely exposed and their presence was inferred mainly from linear topographic depressions across which stratigraphic correlations are tenuous or metamorphic grades are incompatible. In the early 1970s, detailed study in the central Vermilion district showed that early left-lateral faults were offset by northwest- to west-trending right-lateral structures. The right-lateral event appeared to be the more significant of the two; it accorded well with major right-lateral faulting elsewhere in the Superior Province and was consistent with the overall regime of dextral transpression that dominated the tectonic development of the region.

Observations and inferences from recent mapping in the western and central VGB are the basis for revised thinking about the scale, separation sense, and timing of longitudinal faulting. Many of the early strike-parallel faults are regional-scale sinistral structures that were fragmented by later, mostly right-lateral fault zones oriented oblique to their strike. We infer sinistral displacement sense on major longitudinal faults from the map geometry of secondary faults and shear zones, which splay from the main structures and offset marker units. Patterns of sinistral strike-slip duplexes and imbricate fault splays both indicate dominantly extensional kinematics. Because marker units are rare and displacements on trunk faults may have been very great, we also have used the regional distribution of five generalized rock packages to demonstrate offsets. This mega-stratigraphic approach has led us to recognize a fundamental stratotectonic break within the VGB (labelled LLSD on Fig. 1) that divides a northern terrane from a southern one. Although the significance of this break remains to be determined, it clearly is an early feature that has been disrupted by sinistral fault displacements. Left-lateral faulting occurred after peak metamorphism because metamorphic isograds are displaced at fault boundaries. Post-kinematic, alkalic plutons that are spatially associated with some longitudinal faults are locally inferred to have been emplaced in extensional rhombochasms within sinistral strike-slip duplexes. Although unproven, it is probable that some of the sinistral faults occupy parts of the earlier structures, including the medial stratotectonic break within the VGB supracrustal sequence.

The presence of kinematically complex longitudinal fault systems in the VGB is consistent with recent interpretations of greenstone belts as the remnants of accreted arc-trench systems. Phanerozoic accretion of arc-trench systems produces linear blocks of diverse rock suites that are separated and internally segmented by thrust and wrench faults. Having recognized some aspects of this deformational style in the VGB, we now can speculate about the broader paleotectonic and stratigraphic evolution of the belt by "destraining" major fault displacements.

Support for mapping and geophysical data were provided by

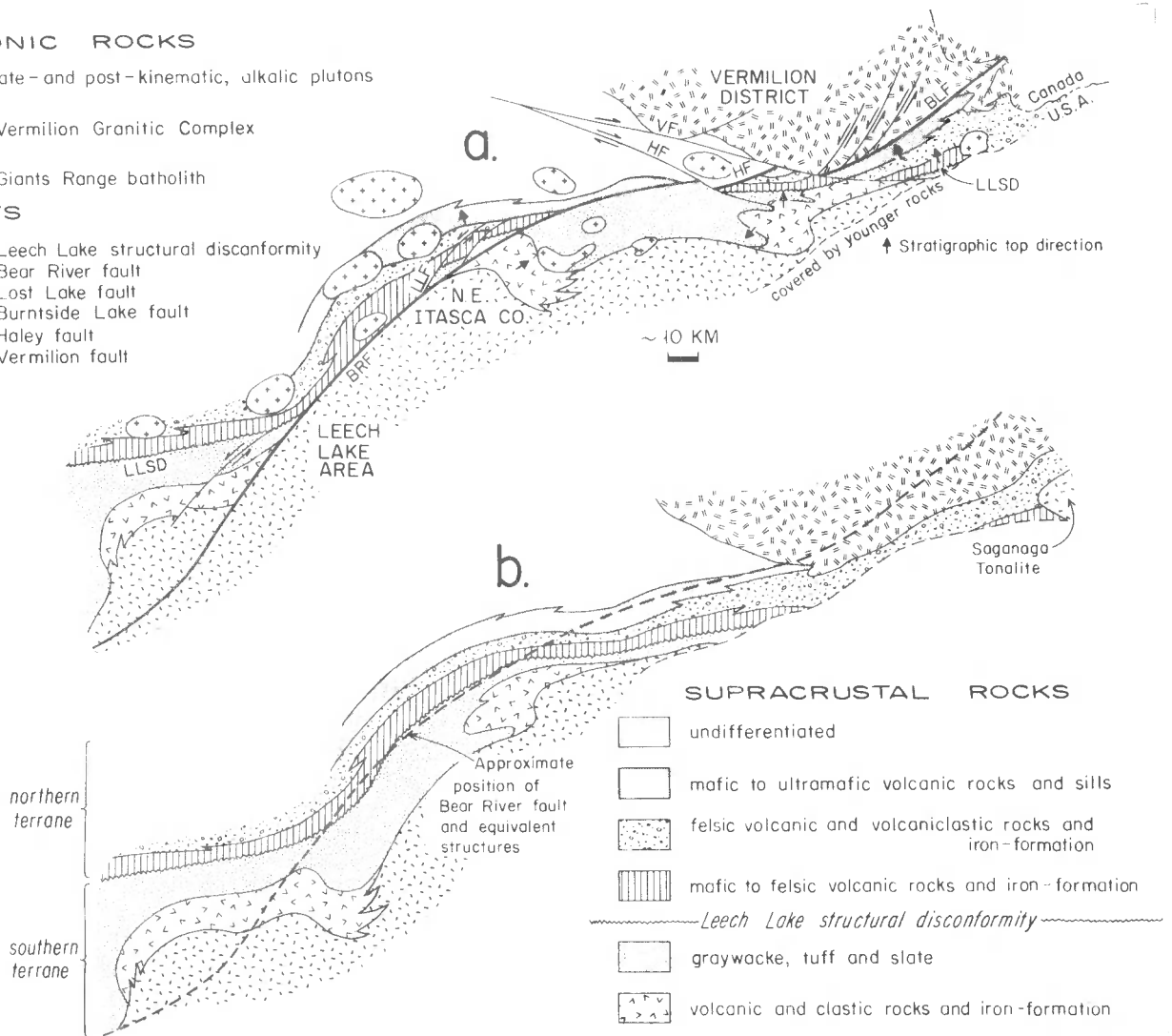
- (1) Mineral Diversification Program of the Minnesota Legislature administered by the Minerals Coordinating Committee.
- (2) Legislative Commission on Minnesota Resources
- (3) CUSMAP Program of the U.S. Geological Survey

#### PLUTONIC ROCKS

-  late- and post-kinematic, alkalic plutons
-  Vermilion Granitic Complex
-  Giants Range batholith

#### FAULTS

- LLSD Leech Lake structural disconformity
- BRF Bear River fault
- LLF Lost Lake fault
- BLF Burntside Lake fault
- HF Haley fault
- VF Vermilion fault



## Structure of the northern block of the Ishpeming greenstone belt, Marquette County, Michigan

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The northern block of the Ishpeming greenstone belt is dominated by tholeiitic pillowed basalt flows with minor massive flows and subordinate pyroclastic and sedimentary rocks and covers  $150 \text{ km}^2$  in north-central Marquette County, Michigan. There are at least two major Archean deformational events: (1) recumbent folding about east-west axes ( $D_1$ ) and (2) upright folding about east-west axes ( $D_2$ ). These deformational events resulted in folds with amplitudes and wavelengths measured in kilometers and a Z-shaped pattern of the distribution of stratigraphic units. Gneissic granitoids that bound the block were intruded during  $D_1$  and metamorphosed the surrounding basalt to amphibolite grade. Granodiorite stocks and quartz and quartz-feldspar porphyritic rhyolite dikes intrude the basalt in and adjacent to shear zones. These felsic intrusions are interpreted as part of the same magmatic event and both were probably emplaced during  $D_2$ .

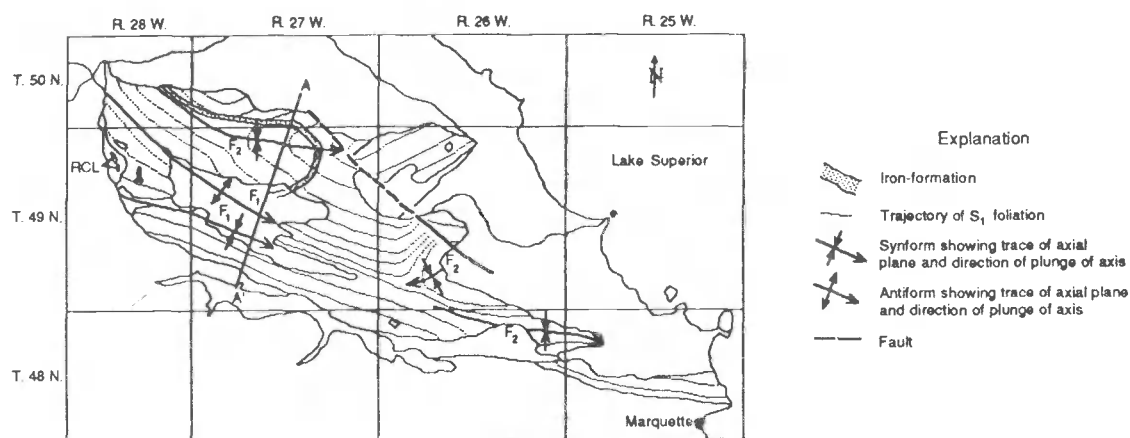


**Figure 1.** Sketch map showing  $S_1$  foliation trajectory,  $F_1$  and  $F_2$  folds, outcrop pattern of the iron-formation unit, and major fault in the eastern end of the northern block. RCL - Rocking Chair Lakes.

The youngest folds ( $F_2$ ) control the overall Z-shaped pattern of stratigraphic units. Since sedimentary and volcanoclastic rocks are rare,  $F_2$  folds are best defined by the folding of  $S_1$  (fig. 1). In the southeast there are two smaller folds that may be controlled by the bounding gneissic granitoids. At the northwest end of the belt,  $L_1$  lineations plunge

moderately to the southeast and  $S_1$  is deformed by an upright, tight to isoclinal southeast-plunging  $F_2$  synform verging to the southwest. Further to the east, along the same fold,  $L_1$  plunges shallowly to the east and  $S_1$  forms an upright, open, shallow easterly plunging  $F_2$  synform; while bedding ( $S_0$ ) forms an open synformal anticline plunging shallowly to the west (note that the fold plunge direction indicated in fig. 1 is for folded  $S_1$  foliation). This apparent contradictory fold geometry is produced by folding  $S_0$  and  $S_1$  surfaces which are not parallel.  $L_1$  in this area is nearly flat lying; the plunge of folded bedding is less than  $10^\circ$  to the west, and the plunge of folded  $S_1$  is less than  $10^\circ$  to the east. The contrary plunge of fold surfaces may be exacerbated by scissors motion along shear zones.

The oldest folds ( $F_1$ ) can be observed northeast and southeast of Rocking Chair Lakes (fig. 1), where the outcrop pattern of a pyroclastic unit and gabbro sills define  $F_1$  folds. The southern  $F_1$  fold is a synformal anticline and the northern  $F_1$  fold is an antiformal syncline. Both folds are tight to isoclinal, upright, and plunge moderately to the southeast. In the vicinity of the fold hinges, bedding is normal to  $S_1$ ,  $S_1$  is axial planar, and  $L_1$  plunges moderately to the southeast. Further to the east,  $L_1$  and  $F_1$  folds plunge shallowly to the east.

The development of folds in the northern block is shown schematically in figure 2. During  $D_1$ , large-scale recumbent, tight to isoclinal  $F_1$  folds were developed (fig. 2a). Subsequently, during  $D_2$ ,  $F_1$  folds were refolded forming isoclinal to open, upright  $F_2$  folds (fig. 2b) accompanied by shearing (fig. 2c). This deformational sequence maintained the relative  $S_0$ - $S_1$  angular relationship observed (i.e.  $S_1$  typically dips more

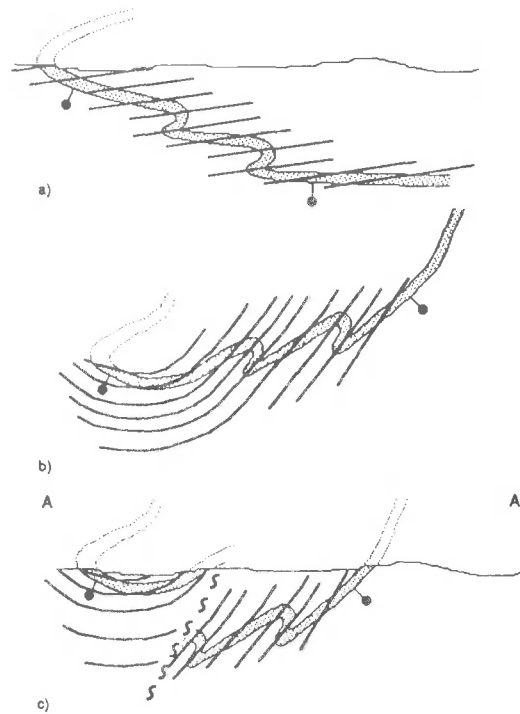


Figure 2. Schematic cross-section of the northern block showing fold development and relationships of bedding and  $S_1$  foliation. a) Early recumbent folding during  $D_1$ , b) open folding about east-west axes during  $D_2$ , and c) late-stage shearing associated with  $D_2$ . Bar and ball symbol indicate local stratigraphic tops.

steeply to the north than  $S_0$ ), which is consistent with the exposed lower limb of the  $F_1$  recumbent fold (fig. 2c). A similar sequence of deformational events is also observed in northern Minnesota (Bauer, 1985; Huddleston et al., 1988).

This project was partially funded by a grant from the Michigan Geological Survey and the COGEOMAP program of the U.S. Geological Survey.

#### References

- Bauer, Robert L., 1985, Correlation of early recumbent and younger upright folding across the boundary between an Archean gneiss belt and greenstone terrane, northeastern Minnesota: *Geology*, v. 13, p. 657-660.
- Huddleston, P.J., Schultz-Ela, D., and Southwick, D.L., 1988, Transpression in an Archean greenstone belt, northern, Minnesota: *Can. J. Earth Sci.* 25, p. 1060-1068.

## ORIGIN AND PETROLOGY OF IRON SILICATE-RICH BODIES IN THE BIWABIK IRON FORMATION, MINNESOTA

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Two distinct 'bodies' of taconite containing large amounts of iron silicates and minor amounts of magnetite occur near Keewatin, Minnesota. Data obtained during thin-section and X-ray studies lead to the conclusion that the bodies are remnants of "original" iron formation which did not develop magnetite during lithification and metamorphism.

The silicate bodies occur in the upper 20 to 70 feet (6 to 21 m) of the Lower Cherty member of the Biwabik Iron Formation. The north body is 2200 feet (671 m) long, 480 feet (146 m) wide, and 40 feet (12.2 m) thick. The south body is located 800 to 1000 feet (244 to 305 m) south of the north body and has a minimum length of 2300 feet (701 m), is 1050 feet (320 m) wide, and 40 feet (12.2 m) thick. Both bodies are located in the same stratigraphic horizon.

Taconite comprising the silicate bodies is grouped into three (3) phases -- silicate taconite, transitional silicate taconite, and silicate-rich taconite -- based on the amounts of iron silicates and magnetite present. Silicate taconite is highest in iron silicates (generally 40 to 50 percent, may be up to 90 percent) and lowest in magnetite (2 to 4 percent) while silicate-rich taconite is highest in magnetite (15 to 20 percent) and lowest in iron silicates (15 to 20 percent). Silicate-rich taconite and transitional silicate taconite can be economically processed but silicate taconite cannot.

The boundary between the silicate bodies and surrounding magnetite taconite is gradational and occurs in a 6 to 10 foot (1.8 to 3.0 m) zone. The boundary between the transitional zone and surrounding magnetite taconite is placed where the first distinct greenish tinge is seen in the magnetite taconite; the exact location of the boundary between the transitional zone and the silicate taconite is uncertain.

A change in texture and mineralogy is seen in the transition from silicate taconite to magnetite taconite. In silicate taconite, the iron silicate granules are usually unaltered to partially altered and consist dominantly of minnesotaite (primary?), with lesser amounts of greenalite (primary) and/or colorless minnesotaite needles (secondary); small amounts of magnetite occur along granule outlines. In the transitional zone, silicate granules are more altered as distance from the silicate body increases and the amount of original iron silicates and secondary minnesotaite needles decreases while the amount of magnetite increases. In magnetite taconite, granules consist dominantly of chert with minor amounts of iron silicates (minnesotaite, stilpnomelane, and possible chlorite) and carbonates. Grains and aggregates of magnetite occur along granule outlines. Magnetite and minnesotaite needles are thought to develop during low grade metamorphism. Because little magnetite is found within the silicate bodies, the silicate bodies are considered remnant areas of iron formation which resisted alteration into magnetite taconite.

Carbonaceous material, permeability, heat flow, and change in bulk chemistry may have acted as factors in determining development of the silicate bodies within the iron formation. Of these, a change in magnesium content is thought to be the dominant factor. A higher magnesium content stabilizes iron silicates relative to magnetite and minnesotaite relative to greenalite. As a result, magnesium-rich areas in a silicate-rich iron formation would be better able to withstand higher temperatures before altering to magnetite taconite than would an area with a lesser content of magnesium. The source of the magnesium may either have been primary, possibly a more magnesium-rich sediment, or secondary, with enrichment during diagenesis or low-grade metamorphism.

Geology of Presque Isle Point, Marquette, Michigan:  
a Second Look

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A longer series of events is recorder by outcrops along the Archean - Jacobsville contact than previously reported (Kalliokoski, 1975; Lewan 1975). A probable lower Proterozoic unconformity extends across a basement of Archean serpentinite, granite, and diabase. The serpentinite is covered by a chloritic paleosol and the granite by an aluminous one. The next event was quartz-carbonate alteration, as white veins 1-20mm thick along the shear polygons in serpentinite, and as fine-grained impregnations in serpentinite and granodiorite (fig. 2). Texturally and compositionally the altered rocks resemble "Palmer Gneiss", an enigmatic alteration product described by Gair and Simmons (1969) from the Negaunee iron-formation footwall. At the point the early alterations in serpentinite are cut by locally abundant, predominantly vertical, slightly branching veins of red, fine-grained, banded, colloform quartz (jasper), with no fluid inclusions or wallrock alteration (fig. 3). This triple paragenesis is known from Archean basement rocks below an iron-formation also at and near Huron River (Kalliokoski and Lynott, 1986).

Its geographic and stratigraphic proximity to iron-formation suggests that the quartz-carbonate alteration is a wide-spread subaqueous accompaniment iron-formation deposition which, in this instance, affected basement rocks exposed along the footwall unconformity (Kalliokoski and Lynott, 1986). I would like to suggest further that the jasper veins represent hydrothermal feeders which transported iron into the overlying early Proterozoic sea.

The succeeding events were uplift, erosion of the presumed Lower Proterozoic cover, and the development of a 10-50 cm blanket of regolith (eluvium) which overlay an active soil layer on the Archean basement (fig. 4). The eluvium is an unsorted, matrix-supported breccia. It consists of angular, elongate clasts (up to 10 x 25 cm) derived from the red, white, and grey veinlets in the serpentinite, in a fine grained matrix. There are also clasts of quartz-carbonate altered serpentinite. Locally the clasts are imbricated, indicative of down-slope solifluction.

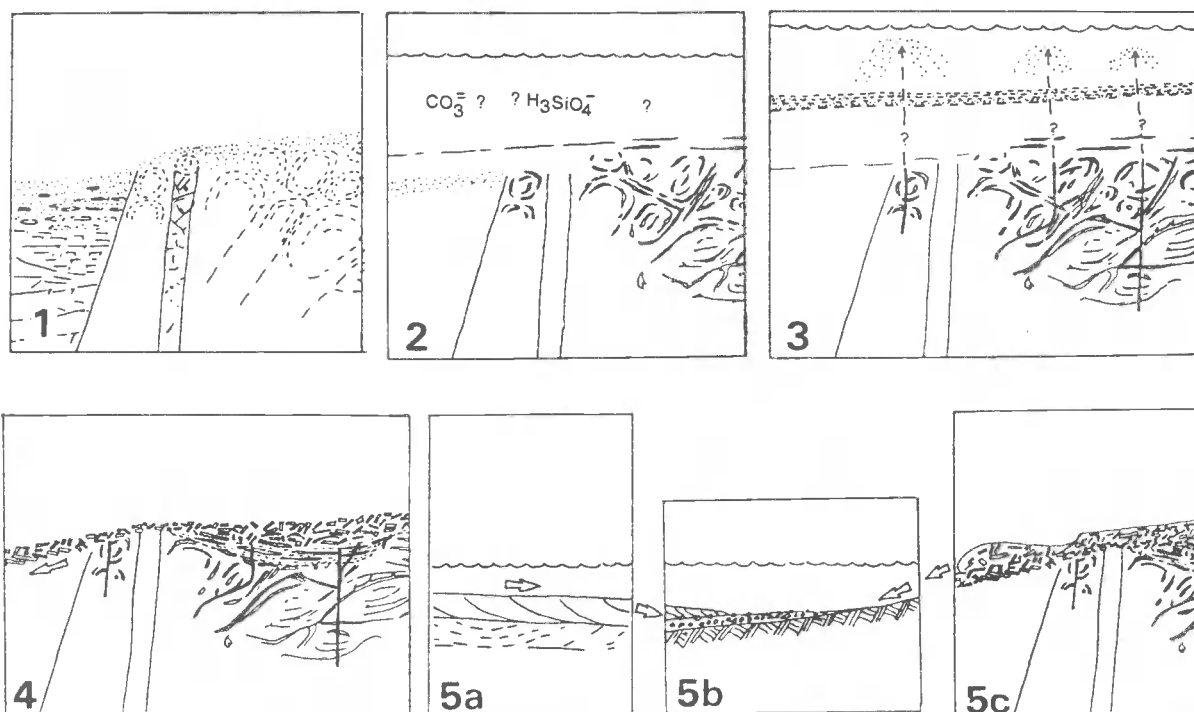
During deposition of the Jacobsville Sandstone the eluvial blanket was unconsolidated. As proof of this, on the west and north sides of the point are 2-60 cm x 2-50 m beds of breccia that underlie, interfinger with, and/or obliquely truncate sandstone beds. This breccia is identical in composition to the eluvium but the thinnest (1-10 mm), most fragile vein segments

were broken during transportation. The breccia beds formed from mudflows off the serpentinite paleo-hill, coeval with Jacobsville sedimentation (fig. 5 a, c).

The thin Jacobsville section (0-4 m) consists of sheets of sandstone, silty shale, minor fine-grained conglomerate, and breccia exposed in small scarps and broad, flat outcrops (fig. 6). Trough beds, foresets, current lineations and rare shale rip-ups are predominant features. Current directions indicate that the sandstones transgressed across the basement, and that the serpentinite formed a topographic high similar to what we see to-day. The sandstone contains abundant feldspar and quartz, and pebble beds contain clasts of feldspar, pointing to a granitic provenance. Some of the quartz pebbles show a highly polished surface, suggestive of wind action at the source.

After Jacobsville deposition the eluvial blanket and breccia beds were cemented by silica. The weathered zone along the top of the basement became compacted and the vertical jasper veins crossing it were vertically shortened (fig. 7). To-day this zone is well into its third cycle of weathering and erosion.

References available from author



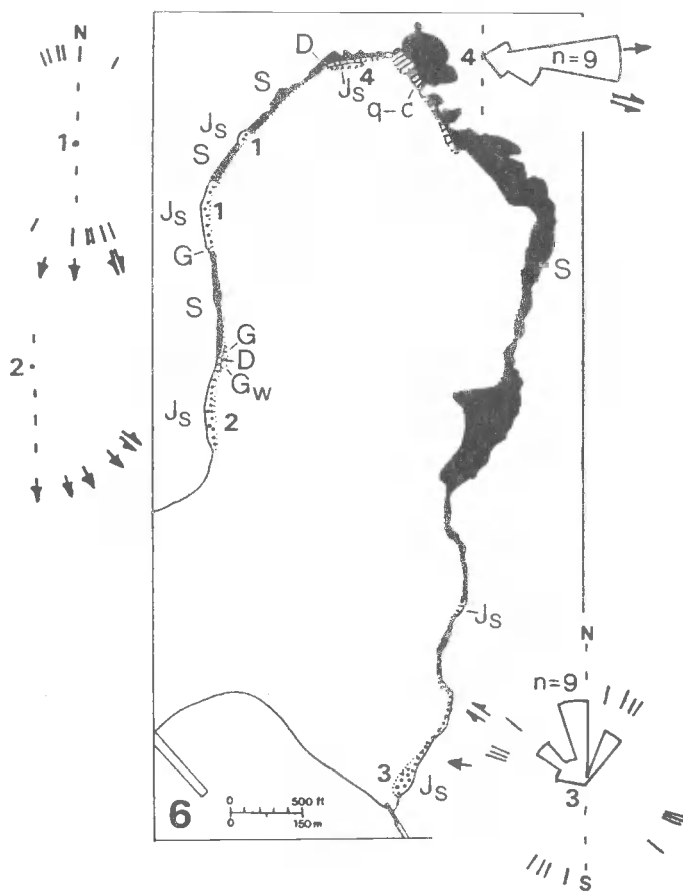
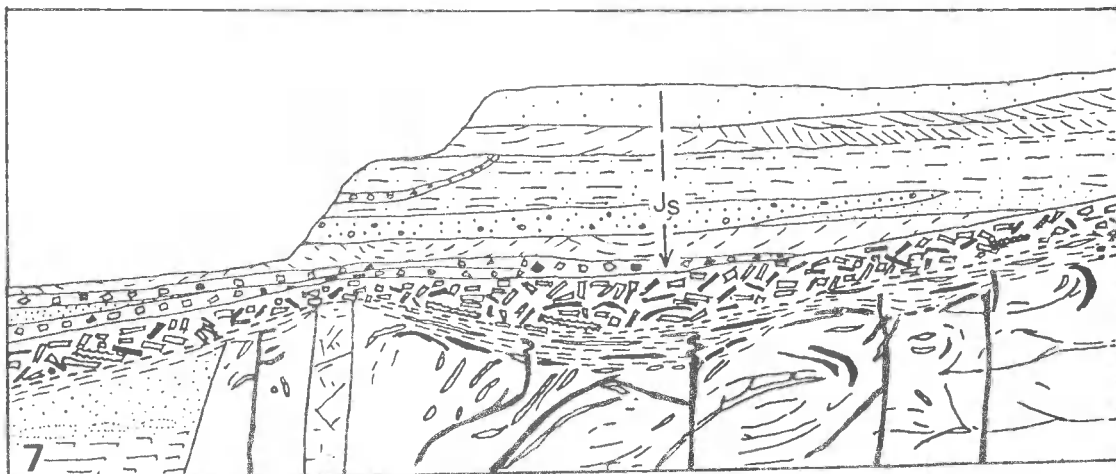


Figure 6. Geologic map of Presque Isle.  
 S, serpentinite;  
 q-c, quartz-carb.  
 alteration;  
 G, granite; Gw,  
 weathered granite;  
 D, diabase; Js,  
 Jacobsville sandstone;  
 1,2,3,4, location of  
 rose diagrams.  
 On rose diagrams:  
 n, no. of cross-bed  
 readings;  
 dashes, trend of  
 current lineations;  
 arrows, trend of trough  
 axes, top view.



Paleomagnetism of Baraboo Interval Rocks in Wisconsin  
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The Proterozoic Baraboo interval is a sequence of quartz-rich metasedimentary rocks of the upper midwest which include the Baraboo, Barron, McCaslin and Waterloo quartzites of Wisconsin, along with the Sioux Quartzites of Minnesota, South Dakota and Iowa. These quartzites are associated by the similarity of their appearance, although there is no firm evidence of their being time synchronous. In Wisconsin, there are also associated igneous rocks which include granites, rhyolites and diorites. We have continued paleomagnetic studies of this sequence in Wisconsin to better define the time relationships between the metasediments and the igneous rocks. We have recently concentrated on the outcrops at Hamilton Mounds and Baxter Hollow.

Hamilton Mounds is an inlier of Baraboo type quartzite intruded by a granite dated at 1760 m.y. with a distinct alteration zone adjacent to the granite. The granite provided no useful paleomagnetic data because the remanent magnetism is too soft. Alternating field (A.F.) demagnetization removed the remanence by 100 millitesla and the magnetic directions were very scattered. The magnetic characteristics of the altered zone indicate the magnetism is due to fine grain magnetite, probably resulting from the reduction of hematite in the quartzites at the time of intrusion. A.F. and thermal demagnetization studies show only one component of magnetization. The magnetism in the quartzite at Hamilton Mound is typical of the Baraboo type quartzites in Wisconsin. The remanence is carried by hematite, and appears to be diagenetic in origin.

At Baxter Hollow a granite is exposed below the quartzite. A sheared or mixed zone below the quartzite appears to be part of the granite with assimilated quartzite. The contact between quartzite and sheared zone is not exposed but quartzite is located within two meters of the sheared zone. The granite has not been dated but it has been interpreted as being both younger and older than the quartzite. The quartzite and granite at Baxter Hollow were previously analyzed by Mercer (1984) and Kean & Mercer (1986). The granite is typically soft magnetically and of little use for paleomagnetic studies. The quartzites of this area provide good data, with the remanence carried by hematite. In this report we present data from the sheared zone. The sheared or mixed zone is magnetically more complex than the counterpart at Hamilton Mounds, but there is a primary remanent component carried by magnetite.

The magnetic directions and pole positions for these sites are provided in table I.

Table I

| <u>Formation</u>                 | <u>No. of<br/>Samples</u> | <u>Mean<br/>Inc</u> | <u>Mean<br/>Dec</u> | <u>Kappa</u> | <u>Alpha 95</u> | <u>V.G.P.</u> |
|----------------------------------|---------------------------|---------------------|---------------------|--------------|-----------------|---------------|
| Hamilton<br>Mounds<br>Quartzite  | 10                        | 43.9                | 332.5               | 6.8          | 19.9            | 61 N 150 E    |
| Hamilton<br>Mound<br>Mixed Zone  | 7                         | 53.9                | 174.0               | 10.9         | 19.2            | 11 S 84 W     |
| Baxter<br>Hollow<br>Sheared Zone | 10                        | 86.3                | 303.5               | 9.3          | 16.7            | 48 N 98 W     |
| Baraboo<br>Quartzite             | 30                        | 59.1                | 199.3               | 19.9         | 15.4            | 14 S 89 W     |

### Conclusions

When the pole positions obtained in this and other studies are compared to Irvings (1976) polarwander pater for the time range 1650-2200 m.y. We make the following conclusions:

1. The Baraboo Quartzite pole (structure corrected) is very similar to the Hamilton Mound mixed zone and is placed at approximately 1800 m.y. based on the location on the polar wander path. This suggests that the Baraboo Quartzite is at least 1760 years old and probably older.
2. The Baxter Hollow sheared zone pole position would place its age at 1650 m.y. if one accepts its position on the polar wander path. If the pole position is corrected with the same structure corrections used on the quartzite at this site, it comes near the structure corrected quartzite pole. Either result would imply that the intrusive activity is younger than the quartzite, and possibly as young as 1650 m.y., but could be as old as 1760 m.y.
3. The results from Hamilton Mounds also imply that the folding of the quartzite at this site is at least 1760 m.y. old.

## References

Irving, E., 1978, Paleopoles and paleolatitudes of North America and speculations about displaced terrains; Can. J. Earth Sci. Vol. 16, Pp.669-694

Kean, W.F. and D. Mercer, 1986, Paleomagnetism of the Baraboo Quartzite of south Central Wisconsin Geosciences Wisconsin, Vol. 10, Pp. 46-53

Mercer, D., 1984, Paleomagnetism of the Baraboo Quartzite: University of Wisconsin-Milwaukee, M.S. thesis, P. 294

## GEOLOGICAL SETTING AND GEOCHEMISTRY OF THE BUSH LAKE GRANITE IN RELATION TO RARE-ELEMENT PEGMATITES, FLORENCE COUNTY, WISCONSIN

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Rare-element pegmatites in Florence County, Wisconsin have intruded low to moderate pressure, Abukuma-type metasedimentary/metavolcanic facies rocks of the Quinnesec Formation. Numerous lines of evidence indicate the early Proterozoic age Bush Lake Granite is the source for these pegmatites. Field mapping reveals a distinct pegmatite aureole in the Quinnesec Formation northwest/north/northeast of the Bush Lake Granite. Greenberg *et al.*, (1983) interpret the southern Penokean volcanic belt as a complex arc environment. Late tectonic intrusion of the Bush Lake Granite as a second-order diapir occurred after peak regional metamorphism (Sims *et al.*, 1985). According to Cerny *et al.*, (1988), the tectonic environment and timing of granitic intrusion compare favorably with documented fertile granite/pegmatite associations.

Compositionally the Bush Lake Granite is a peraluminous, megacrystic, biotite granite. Upward gradations from biotite granite into pegmatitic leucogranite and potassic pegmatite are common. Pegmatitic facies within the granite contain accessory Mn-rich garnet, tourmaline, beryl, and muscovite. Bulk compositions are silicic, Na-rich (2.84-3.61 wt. % Na<sub>2</sub>O), but are poor in Fe, Mg, and Ca (0.29-1.27 wt. % CaO). Li (17-89 ppm), Rb (235-403 ppm), Cs (4.7-13.6 ppm), Ga (7-51 ppm), and Y (7-49 ppm) are enriched, while Ba (34-95 ppm) and Sr (21-89 ppm) are depleted relative to barren granites. High fractionation is suggested by low Rb/Sr (17.5-1.9), Ba/Rb (2.9-0.17), Mg/Li (50.5-4.5), and K/(Cs x 100) (100-17) ratios. Bush Lake Granite K/Rb ratios are low (172-91), but decrease outward to 7.79 in albitized, Li-rich pegmatites (Koehler, 1989).

### REFERENCES CITED

- Cerny, P. and Meintzer, R.E., 1988, Fertile granites in the Archean and Proterozoic fields of rare-element pegmatites: crustal environment, geochemistry, and petrogenetic relationships, *in* Taylor, R.P. and Strong, D.F., eds., Recent advances in the geology of granite-related mineral deposits, The Canadian Institute of Mining and Metallurgy, sp. pub. 39, p. 170-206.
- Greenberg, J.K. and Brown, B.A., 1983, Lower Proterozoic volcanic rocks and their setting in the southern Lake Superior district, *in* Medaris, L.G., Jr., ed., Early Proterozoic geology of the Great Lakes region, Geol. Soc. Am. Memoir 160, p. 67-84.
- Koehler, S.R., 1989, A possible Ta-bearing province in Florence County, Wisconsin [abs.]: GSA Abstract with Programs, v. 21, #4, p. 39.
- Sims, P.K., Peterman, Z.E., and Schulz, K.J., 1985, The Dunbar Gneiss-granitoid dome: Implications for early Proterozoic tectonic evolution of northern Wisconsin: Geol. Soc. Am. Bull., v. 96, p. 1101-1112.

## WAS THE PENOKEAN OROGENY A BI-POLAR EVENT?

Gene L. LaBerge, Geology Department, University of Wisconsin Oshkosh, Oshkosh, WI 54901, and U. S. Geological Survey, and John S. Klasner, Geology Department, Western Illinois University, Macomb, IL 61455, and U. S. Geological Survey.

There is now widespread agreement that the Penokean orogeny was the result of plate tectonic activity. Most authors suggest that evolution of the orogen in Michigan and Minnesota began with a rifting phase accompanied by formation of basins and troughs along the passive margin of the Archean Superior craton, and was accompanied by deposition of rocks of the Marquette Range Supergroup in Michigan and equivalent Animikie Group rocks in Minnesota (Schulz and others, in press). However, Hoffman (1987) and Southwick and others (1988) have recently suggested that the iron-bearing sequences formed in foreland basins during accretion. Nd isotope studies on the Biwabik and Negaunee Iron-formations suggest deposition of these rocks about  $2100 \pm 52$  Ma (Gerlach and others, 1988). Rifting was followed by southward subduction of oceanic crust to form the arc-related volcanic and plutonic rocks of the Wisconsin magmatic terranes. These were subsequently accreted to the continental margin on the north between 1900 and 1830 Ma (Sims and others, 1989; LaBerge and others, 1984; Larue and Sloss, 1980; Cambray, 1978). Accretion of the magmatic rocks to the continental margin of the Superior craton about 1,860 Ma (Sims and others, 1989) resulted in northward thrusting of rocks onto the craton (Attoh and Klasner, 1989; Klasner and others, 1988a, 1988b; Holst, 1982, 1984).

Recently, LaBerge and others (in press), LaBerge and Klasner (1989, 1988, 1986) and LaBerge (1986) proposed that a similar sequence of events occurred in central and southern Wisconsin during the Penokean orogeny. Widely scattered areas of quartzite, and locally (at Baraboo) slate, dolomite and iron-formation, are interpreted to be remnants of a once-extensive passive margin succession. Archean rocks of unknown extent are locally exposed in central Wisconsin and are believed to be the basement on which these sedimentary rocks accumulated. Structures in the quartzites indicate south-directed folding and thrusting of the sedimentary rocks (LaBerge and others, in press; Cambray, 1987; LaBerge and Klasner, 1986) onto the Archean rocks. This interpretation is supported by geophysical evidence presented by Cannon and others (1989). We suggest that the 1,750 meter thick sedimentary succession combined with the widespread evidence for south-verging folding and thrusting argues for collision of a substantial mass of rocks - perhaps of micro continent size - with the Proterozoic island arc complex, which is now the Wisconsin magmatic terranes. Sims and others (1989) conclude that this collision occurred about 1,840 Ma.

In the magmatic terrane of north-central Wisconsin (specifically Marathon County) structures are upright - sub-vertical to vertical - (LaBerge and Myers, 1984, 1987) and have

no consistent sense of structural vergence. The magmatic terrane in the Dunbar area of northeast Wisconsin has a strong northerly sense of vergence (Sims and others, 1985). Attoh and Klasner (1989) have suggested that the magmatic rocks in the Dunbar area are para-allochthonous, having been thrust northward onto the buried continental margin. Dismembered ophiolite (Schulz, 1987) in northeast Wisconsin likely represents a remnant of oceanic crust that was thrust onto the continental margin.

Taken together, from southern Wisconsin to northern Michigan (Fig. 1), the Penokean orogen consists of: a deformed remnant of Archean basement overlain by Early Proterozoic platform sediments deformed by south-verging structures; a region of accreted island arc volcanic rocks with upright structures; a region of island arc magmatic and plutonic rocks with north-verging structures; and an Early Proterozoic continental margin with platform sediments and prominent north-verging structures.

The platform sediments and rifted continental margins represent the rifting phase. Formation of an ocean basin is documented by the presence of ophiolite. The island-arc volcanic rocks and plutonic rocks represent the closing phase of the ocean. Final closure resulted in accretion of magmatic rocks to the continental margins along the Eau Pleine and Niagara sutures (Fig. 1) in the south and north respectively. Prominent south-verging structures formed on the continental margin in central Wisconsin and north-verging structures on the continental margin. We contend that interpretations of the Penokean orogeny as north-directed only do not accurately represent the event--the evidence indicates that it was bi-polar.

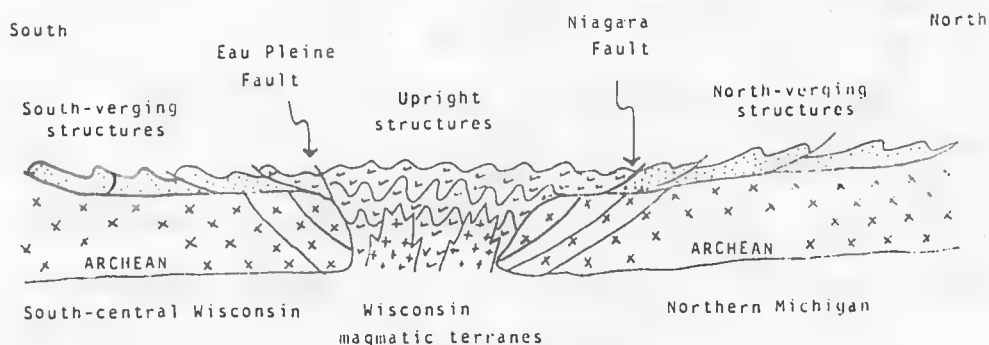


Figure 1. Sketch showing major features in a north-south transect of the Penokean orogen.

# References Cited

- Attoh, K., and Klasner, J. S., 1989, Tectonic implications of metamorphism and gravity field in the Penokean orogen of northern Michigan: Tectonics, v. 8, p. 911-933.
- Cambray, F. W., 1978, Plate tectonics as a model for the environment of deposition and deformation of Early Proterozoic (Precambrian) of northern Michigan. Geol. Soc. Amer., Abstracts with programs, No. 10, p. 376.
- Cambray, F. W., 1987, The Baraboo Syncline: the shape and refolding explained as a result of superimposition of simple shear on a pre-existing fold: Abstract, Geol. Soc. of Amer., Abstracts with programs, p. 192.
- Cannon, W. F., Schulz, K. J., Hinze, W. J., and Green, A. G., 1989, Precambrian terranes beneath northern Lake Michigan defined by seismic and gravity analysis; Institute on Lake Superior Geology, v. 35, Part 1, Abstracts, p. 14, 15, Duluth, MN.
- Gerlach, D. C., Shirey, S. B., and Carlson, R. W., 1988, Nd isotopes in Proterozoic iron-formations: Evidence for mixed-age provenance and depositional variability; Abstract, Am. Geophys. Union Trans., EOS, v. 69.
- Hoffman, P. F., 1987, Early Proterozoic Foredeeps, Foredeep magmatism, and Superior-type iron-formations of the Canadian Shield, in Proterozoic lithospheric evolution, edited by A. Kroner, American Geophysical Union, Geodynamics Series, No. 17, pp. 85-98.
- Holst, T. B., 1982, Evidence for multiple deformation during the Penokean orogeny in the Middle Precambrian Thomson Formation, Minnesota: Canadian Journal of Earth Sciences, v. 19, p. 2043-2047.
- Holst, T. B., 1984, Evidence for nappe development during the Early Proterozoic Penokean orogeny, Minnesota: Geology, v. 12, p. 135-138.
- Klasner, J. S., Ojakangas, R. W., Schulz, K. J., and LaBerge, G. L., 1988, Widespread evidence for Early Proterozoic overthrusting in the Penokean orogen of northern Michigan, Abstract, Geol. Assoc. of Canada and Min. Assoc. of Can., Programs with abstracts, v. 13, p. A67.
- Klasner, J. S., Sims, P. K., Gregg, W. J., and Gallup, C., 1988b, A structural traverse across a part of the Penokean orogen, illustrating Early Proterozoic overthrusting in northern Michigan; in Schulz, K. J., (ed.) v. 2, Field Trip Guidebooks 34th Annual Institute on Lake Superior Geology, Marquette, Michigan, p. C1-C36.
- LaBerge, G. L., 1986, The Proterozoic geology of the Lake Superior region: in LaBerge, G. L., Attig, J. W., and Mode, W. N., Guidebook, Tri-State Geological Field Conference, Wausau, Wisconsin, p. 1-29.
- LaBerge, G. L., and Klasner, J. S., 1986, Evidence for a major south-directed Early Proterozoic thrust sheet in south central Wisconsin: Abstract, Geol. Soc. of Amer., Annual Meeting, San Antonio, Texas.
- LaBerge, G. L., and Klasner, J. S., 1988, The Baraboo Quartzite: a new look at an old problem: Abstract, 34th Annual Institute on Lake Superior Geology, Marquette, Michigan, p. 62-64.
- LaBerge, G. L., and Klasner, J. S., 1989, Tectonic implications of the structure and stratigraphy of quartzites in central and southern Wisconsin: Abstract, 35th Annual Institute on Lake Superior Geology, Duluth, Minnesota, p. 49-50.
- LaBerge, G. L., Klasner, J. S., and Myers, P. E., in press, New observations on the age and structure of Proterozoic quartzites in Wisconsin: in Sims, P. K., and (ed.), contributions to the Precambrian geology of the Lake Superior region: U. S. Geol. Sur. Bull. 1904-B.
- LaBerge and Myers, 1984, Two Early Proterozoic successions in central Wisconsin, GSA Bulletin, v. 95, pp. 246-253.
- LaBerge, Schulz, and Myers, 1984, The plate tectonic history of central Wisconsin, Abstract, 30th Annual Institute on Lake Superior Geology, Wausau, WI
- Schulz, K. J., and Sims, P. K., and Morey, G. B., in press, Tectonic synthesis, Penokean orogen, and associated epicratonic rocks: Geol. Soc. of America DNAG volume, C-2, Precambrian, conterminous U.S.
- Schulz, 1987, An early Proterozoic ophiolite in the Penokean orogen: Abstract, Geol. Assoc. of Can., abstracts with programs, v. 12, p. 87.
- Sims, P. K., Van Schmus, W. R., Schulz, K. J., and Peterman, Z. E., 1989, Tectonostratigraphic evolution of the Early Proterozoic Wisconsin magmatic terranes of the Penokean orogen: Canadian Journal of Earth Sciences.
- Sims, Peterman, and Schulz, 1988, The Dunbar gneiss-granitoid dome; implications for Early Proterozoic tectonic evolution of northeastern Wisconsin: Geol. Soc. of Amer. Bulletin, v. 96, p. 1101-1112.
- Southwick, D. L., Morey, G. B., and McSwiggen, P., 1988, Geological map (scale: 1:250,000) of the Penokean orogen, central and eastern Minnesota, and accompanying text, Minn. Geol. Survey, Report of Investigations RI-37.

## GEOLOGY AND ECONOMIC POTENTIAL OF NORTHERN MICHIGAN GRAPHITE

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Recent cooperative research by Michigan Technological University (MTU) and the Michigan Geological Survey (MGS) was undertaken to determine the quantity, quality and distribution of the carbon-rich graphitic slate resource present in northern Michigan. The ultimate goal of this research was to provide mineralogical, chemical and geophysical data that will aid in identifying uses that will lead to commercial development of this vast and, as-yet, untapped resource.

The graphite is present in the early Proterozoic Lower Slate Member of the Michigamme Formation in the Baraga Group sediments. Earlier investigations (Hwang *et. al.*, 1986) suggest that 3 billion tons of graphite-bearing slate, grading 20-25% carbon, exist at mineable depths in a 30-mile long belt in Baraga and Marquette counties (Fig. 1). Compositionally, the slate consists predominately of fine silica (43-53%), carbon (2-47%), iron oxide (10-14%) and alumina (7-11%). The slate contains relatively low concentrations of the alkaline earth metal oxides CaO (0.4-0.7%) and MgO (1-3%). Similarly, concentrations of the alkali metal oxides K<sub>2</sub>O (2-3%) and particularly Na<sub>2</sub>O (<0.12%) were quite low. This composition is consistent with deposition under reducing anaerobic conditions with minor or no clastic input.

This and earlier studies (Hwang *et. al.*, 1986) (Kramer *et. al.*, 1987) have determined that the graphite is of the "amorphous" or cryptocrystalline variety. Typical grain size, as determined by electron microscope, ranged from 1 to 3 microns. Carbon analyses of 90 samples collected from drill core at the MGS core repository in Marquette, MI, yielded a range of 2 to 47% carbon. There appeared to be no correlation between graphite (carbon) concentration and metamorphic grade. In drill cores with high sample density, there appeared to be a cyclical increasing and decreasing of carbon content with depth. This could suggest a cyclical depositional pattern. Thus, graphite content might be function of stratigraphic position, though more research is required to support this interpretation.

The reducing conditions under which the carbon-rich slate was deposited, makes it an ideal "trap" for a variety of trace and rare earth elements. Trace element analysis for 54 elements showed the presence of a very large number of rare earth, alkaline, base metal and the precious metals, gold and silver. Vanadium is the most abundant of the trace elements with a range of 1300-2000 ppm. Vanadium content is positively correlated to carbon content. Although, there is a fairly wide divergence in the absolute concentration of the various trace elements, the ratios between trace elements are amazingly uniform for composite samples taken over a 30-mile zone (Fig. 1) (Lagowski and Johnson, 1989). Based on this observation, a similar chemical environment of deposition is inferred. Also, metamorphic overprinting has not altered these geochemical relationships.

The geology of the graphitic Lower Slate Member is structurally complex due to multiple deformational events related to the 1850 Ma Penokean Orogeny (Klasner, 1978) and later 1100 Ma Keweenaw rifting. Extensive glacial overburden makes conventional outcrop mapping virtually impossible. Fortunately, the graphitic strata are highly conductive and can be detected by electrical geophysical methods. In order to determine which geophysical technique or combination of techniques would provide the most accurate data for future exploration, a multi-component geophysical survey was conducted over an area of known geology. The results of this investigation indicate that the best electrical methods are horizontal loop electromagnetics and very low frequency electromagnetics using the EM16R, used in combination. The use of geophysics in conjunction with drilling is the only suitable means of defining graphite-rich strata.

Utilization studies conducted at Michigan Tech show several promising uses for Upper Michigan graphite (Johnson *et. al.*, 1989). One potential "as is" use for this material is as a high quality shale substitute in the manufacture of portland cement. The abundant graphite-rich rock may also be considered as an unrecognized and untapped fuel resource. Compared on an equal volume basis with coal, rock grading 30% graphite is estimated to be roughly equivalent to the heating value of low grade (60% carbon) coal. If the graphite material can be beneficiated from the 15 to 25% carbon range to 80+%, this material would also be an ideal metallurgical reductant for the Pelletech Process of making self-fluxing iron ore pellets.

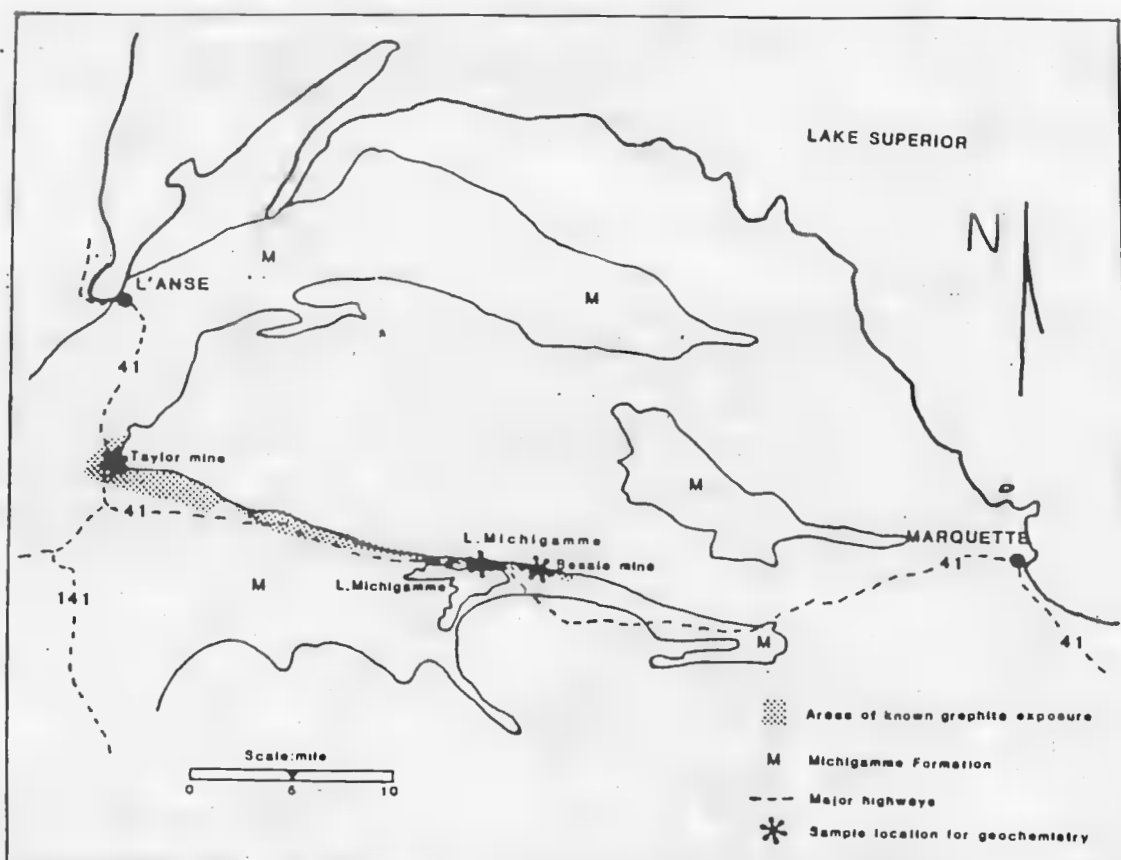


Figure 1. Geologic map of western Upper Peninsula, Michigan showing graphite-rich slate and geochemical sample locations.

#### REFERENCES CITED

- Hwang, J.Y., Carlson, D.H., Johnson, A.M., and VanAlstine, J. (1986), "Preliminary Investigation of Graphite Resources in Michigan", 115th Annual Mtg., SME AIME, New Orleans, LA Preprint.
- Johnson, A.M., Carlson, D.H., and Cho, P. (1989), "Utilization of Upper Michigan Graphite Resources", Geological Survey Division, Michigan DNR Open File Report, -89,
- Klasner, J.S. (1978), "Penokean Deformation and Associated Metamorphism in the Western Marquette Range, Northern Michigan", Geological Society of America Bulletin, V.89, pages 711-722.
- Kramer, R.S., Hwang, J.Y., and Johnson, A.M. (1987), "A Mineralogical and Chemical Study of the Graphitic Lower Slate Member, Michigamme Formation, Marquette and Baraga Counties, Michigan", Geological Survey Division, Michigan DNR Open File Report -87.
- Lagowski, J. And Johnson, A.M. (1989), "Geologic Investigation of Graphite-Rich Strata in the Michigamme Formation--Baraga and Marquette Counties, Michigan", Geological Survey Division, Michigan DNR Open File Report -89.

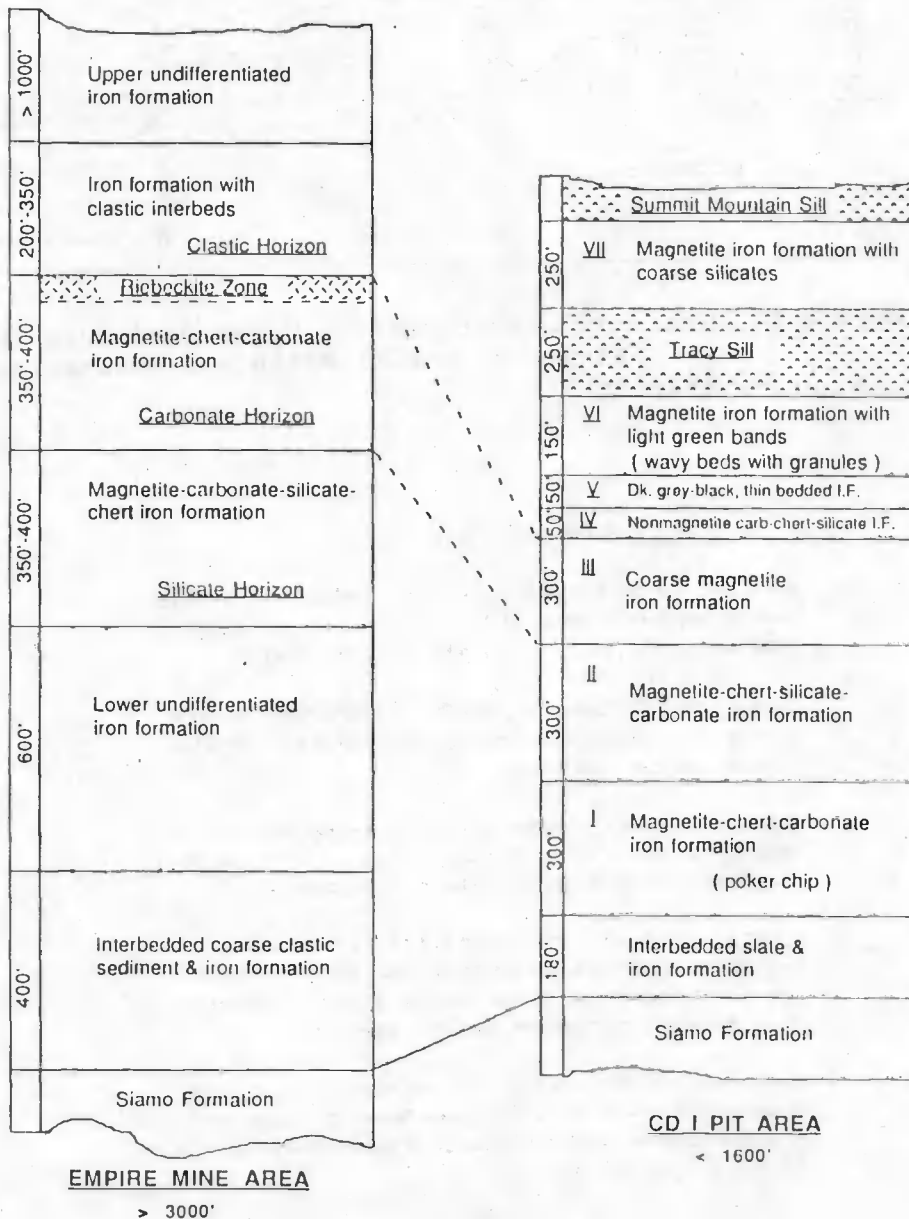
# STRATIGRAPHY OF THE NEGAUNEE IRON FORMATION, EASTERN MARQUETTE RANGE, MICHIGAN

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## Introduction

The stratigraphic subdivisions of the Negaunee iron formation in the Empire Mine area (Secs. 19 & 20) differ substantially from the iron formation in the CD I Pit area (Sec. 18) and to the north in Sec. 5, 6, 7 & 8. The Empire Mine area, which comprises over 3000' of continuous iron formation above the Siamo Formation, is informally subdivided into 5 units based on mineralogy, texture, and metallurgy. The Empire Pit is confined to the silicate, carbonate, and clastic units which occupy an 1100' interval (1000' to 2100') above the Siamo contact. The iron formation in the CD I Pit area and to the north is less than 1600' thick between the Siamo Formation and the Summit Mountain sill. It is subdivided into 7 informal units. The CD I Pit is located in the coarse magnetite unit (unit III) which occupies a 300' interval from 780' to 1080' above the Siamo Formation.



### Coarse Clastic Interbeds

The Empire mine section includes a 400' zone of iron formation and interbedded coarse clastic sediments (greywackes or arkoses) immediately above the Siamo Formation and a 250-300' zone of coarse clastic sediments and iron formation in the clastic horizon which occupies the interval from approximately 1700' to 2000' above the Siamo Formation. The iron formation in the CD I Pit area and north contains no coarse clastic sediments.

### Riebeckite Zone

In the Empire Mine a distinct marker zone of iron formation containing blue riebeckite is found in the upper 150 feet of the carbonate unit. No riebeckite was seen in the CD I Pit area.

### Diabase Sills

In the CD I Pit area the Tracy Sill (250' thick) and the Summit Mountain Sill (500' thick) intrude into the lower 1600' of iron formation. No metadiabase sills intrude the 3000' of iron formation in the Empire Mine area.

### Structure and Oxidation

The Empire Mine sequence strikes NS to N. 40 E. and dips 30-45 NW. It is offset by a number of WNW faults with less than 100' of displacement. Very little oxidation is associated with the faults. The iron formation in the CD I pit area strikes NS and dips 30-35 W. It is cut by EW and NW faults with less than a few hundred feet displacement. Very little oxidation is apparent. North of the CD I Pit in sections 5, 6, 7, and 8 the iron formation strikes N. 35-40 W. and dips 20-50 SW. Numerous major EW and NW faults with displacements of over 1000' transect the iron formation. The iron formation is completely oxidized to hematite and limonite and, in places, leached of silica.

### Correlation

Similarities between the Empire and CD I sections are few but include the following:

1. The carbonate unit in the Empire Mine is very similar in mineralogy, texture, and metallurgy to the coarse magnetite unit (Unit III) of the CD I Pit area; however, they differ in thickness and position above the Siamo Formation.
2. Zones up to 50' thick of wavy-bedded iron formation with magnetite rich granules occur in unit VI approximately 100' above the coarse magnetite unit in the CD I Pit area. Stratigraphically this corresponds closely to the position of the clastic horizon which occurs just above the carbonate unit at the Empire Mine.
3. Several thin lenses (less than 2") composed of sand sized quartz grains and stibnomelane occur in the upper undifferentiated unit at the Empire Mine and in unit VI in the CD I Pit area.

### Conclusions

The Empire mine section and the CD I Pit section appear to meet abruptly at 14600' south, between DDH holes 47 and 50 approximately 1200' north of the boundary between secs. 18 and 19. The contact cannot be considered a simple fault because the relationship is not marked by displacement or oxidation but by an abrupt change in stratigraphy and thickness. Contact relationships indicate either a complex fault with great displacement such as the Palmer fault, or an Archean fault zone which was active during deposition of the iron formation and reactivated during the Penokean Orogeny.

## Petrologic and Geochemical Evolution of the Penokean Peavy Pond Complex, Iron County, Michigan

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The Peavy Pond Complex (PPC) is a metamorphosed, composite pluton of Penokean age (1.85 Ga, Van Schmus, personal communication) that intrudes complexly deformed, biotite to sillimanite grade pelitic to quartzose shales and graywackes of the Proterozoic Michigamme Formation (MF) and basic pyroclastics and lavas of the Proterozoic Hemlock Formation (HF). Rocks of the PPC are characterized by the lithologic succession gabbro-diorite-tonalite-granodiorite-granite. Gabbro and diorite are most abundant and are commonly associated with HF wallrocks in the southern portion of the complex. The more silicic tonalites, granodiorites and granites are restricted to outcroppings principally in the northwestern portion of the complex in close proximity to rocks of the MF; these rocks often contain xenoliths of MF and develop locally into migmatites.

The PPC and surrounding area were mapped in excellent detail by Bayley (1959) and Dutton (1968). Bayley interpreted the mafic rocks of the PPC to be products of fractional crystallization of a parental basaltic magma and considered the more silicic phases of the complex to have been derived from variable assimilation of the MF by this parental magma. Bayley's interpretations were based largely on field and petrographic data; due to the lack of uninterrupted outcrops, however, other explanations for the development of the complex must be considered. These include development of each phase of the PPC as a separate magma, variable mixing of magmas, partial melting of wallrocks, or some combination of any of these processes with the fractionation-assimilation process originally suggested by Bayley.

The PPC has potential tectonic significance in that it intrudes rocks considered to represent a passive margin sequence (Larue, 1983; Ueng et al., 1988), a rifted passive margin assemblage (Cambray, 1978), a forearc or backarc basin (Van Schmus, 1976), or a foredeep (Hoffman, 1988; Barovich et al., 1989). Recent studies of the HF volcanics and the associated Kiernan Sills (KS; which lie about 4 km to the north of the PPC) indicate MORB-like geochemical characteristics of these rocks; While these data suggest a MOR-like rift-related origin for these units, they also could be interpreted to reflect a back-arc origin for the HF and KS (Ueng et al., 1988; Wee, 1989). Data derived from analyses of the nearby Badwater (Greenstone) Formation indicates an origin closely related to that of the HF and the KS for these lavas (Cudzillo, 1978; Wee, 1989).

The goals of our study were to determine the processes by which the PPC evolved and to gain insights into the tectonic evolution of this area through geochemical studies of the PPC.

### Major Element Variations within the PPC

Plots the major oxides vs.  $\Sigma\text{FeO}/(\Sigma\text{FeO}+\text{MgO})$  for our PPC data relative to that of the MF, the HF, the KS, the Badwater Fm. and the Northern Wisconsin Arc Complex clearly distinguish mafic phases of the PPC from other units largely on the basis of the higher MgO and lower  $\Sigma\text{FeO}$  concentrations of the PPC rocks. With increasing differentiation, the mafic PPC phases show relatively strong depletions in FeO, MnO, and MgO and corresponding enrichments in  $\text{Al}_2\text{O}_3$ ,  $\text{Na}_2\text{O}$ ,  $\text{K}_2\text{O}$ , and to some extent in  $\text{TiO}_2$ . These trends suggest fractionation of ferromagnesian mineral phases instead of plagioclase. Attempts to apply Pearce Element Ratio Diagrams to test this hypothesis failed as there are no truly conserved major or trace elements in the PPC rocks; this is true for silicic phases of the PPC as well. The more silicic phases of the complex tend to converge towards the compositions of the MF rocks indicating possible interaction of the MF in the evolution of the PPC as suggested by Bayley (1958). Generally higher concentrations of  $\text{K}_2\text{O}$ ,  $\text{SiO}_2$ , and to some extent  $\text{Na}_2\text{O}$  in the silicic PPC phases relative to the MF could be interpreted as resulting from assimilation processes. The elevated concentrations of these elements, however,

could also be explained by partial melting processes involving minimum melts of quartz, potassium feldspar and sodic plagioclase in the MF rocks.

#### Trace Element Variations within the PPC

Mafic rocks of the PPC are distinguishable from other mafic rocks of the region on the basis of trace element abundances as well as by major element concentrations. For example, concentrations of Sc and Co are generally lower and concentrations of Ni, Ta, Ba and Sr are generally higher in the PPC rocks than in the HF, KS metagabbros, or Badwater Fm. Fractionation trends are clearly visible for the transition metal elements Sc, Cr, Co, and Ni in mafic PPC rocks, suggesting removal of phases that preferentially incorporate these elements, perhaps chromite, olivine, pyroxene, or some combination thereof. There is some field evidence in the form of cumulate-like hornblende-rich rocks (ca. 80% Hb) for pyroxene fractionation (metamorphic hornblende after pyroxene); this is the favored starting point for future trace element modelling. Fractionation of oxides, olivine or pyroxene would increase the relative concentrations of Ba and Rb in more differentiated rocks of the complex, consistent with observed trends. The increase of Sr concentration with increasing differentiation supports the assumption of little plagioclase fractionation, since this process would result in a systematic decrease in Sr with increasing fractionation. Limited plagioclase fractionation is also supported by REE data which are characterized by relatively flat, LREE-enriched, profiles and development of only small positive and negative Eu anomalies.

Trace element concentrations of PPC silicic rocks also converge towards the compositions of MF rocks, supporting the hypothesis of MF involvement in the evolution of these rocks. This is discussed further below.

#### Spidergrams

To test the validity of the hypothesis that silicic PPC rocks are related by assimilation or partial melting of MF rocks, we constructed spidergrams (modified from Thompson, 1981) *normalized to average MF*.

Among other things, the spidergrams indicate that rocks of the HF are depleted in LILE and enriched in HFSE relative to MF. The PPC diorites and gabbros appear similar in most respects to the HF rocks; major exceptions are the higher concentrations of Sr and the lower concentrations of Th, P, Y, and Yb in the PPC rocks. The lower Th concentrations in particular are noteworthy in that these values may reflect differences in the relative source regions and/or ascent paths of the PPC and the HF.

The PPC tonalites, granodiorites and granites cluster around the average MF composition. There is only a small overall variation from unity (and thus from average MF) for the PPC tonalites. This could result from 1) large-scale contamination of gabbroic parental magmas by assimilation of extensive amounts of MF or 2) almost complete melting of MF to form the tonalites; the latter hypothesis is broadly consistent with observed major element data. The elevated concentrations of the LILE and LREE, as well as Zr and Hf, in the PPC granites and granodiorites relative to average MF suggest that partial melting processes rather than assimilation processes were dominantly responsible for the production of these rocks; this is consistent with interpretations regarding the major element compositions of these rocks.

#### Tectonic Discrimination

We have so far applied only a few of the many available methods of geochemical discrimination diagrams to the PPC rocks to learn more about the tectonic setting of their origin. AFM diagrams indicate a distinct calc-alkaline trend for all rocks of the PPC. When plotted alone, however, the mafic PPC rocks can be interpreted to reflect indistinctly either a calc-alkaline (arc-derived) trend or a tholeiitic (MORB-like) trend. Inasmuch as the MF rocks are characterized by a distinct calc-alkaline trend, reflecting their derivation from the Wisconsin arc to the south and from the Archean calc-alkaline plutonics to the north and east (see Barovich et al., 1989), it is conceivable that the calc-alkaline trend of the entire PPC suite largely reflects the apparent genetic association of the more silicic phases of the PPC with the calc-alkaline MF.

Plots of  $\text{CaO/TiO}_2$  vs.  $\text{TiO}_2$  and of  $\text{Al}_2\text{O}_3/\text{TiO}_2$  vs.  $\text{TiO}_2$  (Sun and Nesbitt, 1978) suggest the derivation of the PPC from a relatively undepleted mantle source similar to that which produces MORB. The more silicic rocks of the PPC trend into the depleted mantle/arc field in the  $\text{Al}_2\text{O}_3/\text{TiO}_2$  vs.  $\text{TiO}_2$  plot, yet fall beyond the depleted mantle/arc field of the  $\text{CaO/TiO}_2$  vs.  $\text{TiO}_2$  plot. In both cases, however, there is a strong relationship between silicic PPC rocks and those of the MF that once again suggests a genetic nexus.

A MORB-like affinity of the mafic PPC rocks is also indicated by Zr/Y vs. Zr plots (Pearce and Norry, 1979) as well as Ta/Yb vs. Th/Yb plots, however some PPC gabbros could be interpreted to be arc-related on the basis of the Zr/Y vs. Zr diagram. In both diagrams, silicic phases of the PPC plot with rocks of the MF.

There exists at this time no unambiguous explanation for the tectonic setting of the PPC. While it seems clear that the original gabbroic magma was MORB-like, and probably originated in either a MOR-like rift or a back-arc setting, we are unable to distinguish between these environments at this time. To complicate matters further, there is some evidence that suggests that certain PPC gabbros may have originated within a volcanic arc. We cannot unilaterally reject these data due to the relatively close proximity of the northern Wisconsin arc to the PPC, but we believe that the arc-like characteristics of these gabbros could be explained by assimilation of MF. The calc-alkaline arc-like character of the more silicic phases of PPC could also reflect an origin within a volcanic arc environment, however, there appears to be substantial geochemical, petrologic, and petrographic evidence to support the hypothesis that these rocks were derived largely from or through assimilation of the calc-alkaline MF.

### References

- Barovich, K.M., Patchett, P.J., Peterman, Z.E., and Sims, P.K., 1989, Nd isotopes and the origin of the 1.9-1.7 Ga Penokean continental crust of the Lake Superior region: *Geological Society of America Bulletin*, v. 101, p. 333-338.
- Bayley, R., 1959, *Geology of the Lake Mary quadrangle, Iron County, Michigan*: U.S. Geological Survey Bulletin, v. 1077, 112 p.
- Cambray, F.W., 1978, Plate tectonics as a model for the environment of deposition and deformation of the Early Proterozoic (Precambrian X) of northern Michigan: *Geological Society of America Abstracts with Programs*, v. 10, no. 7, p. 376.
- Cudzillo, T.F., 1978, *Geochemistry of Early Proterozoic igneous rocks, northeastern Wisconsin and upper Michigan*: Ph.D. thesis, Lawrence, KS, University of Kansas, 202 p.
- Dutton, C., 1968, *Geology of the Florence area, Wisconsin and Michigan*: U.S. Geological Survey Professional Paper 633, 54 p.
- Hoffman, P.F., 1988, Animikie Group: A Penokean foredeep?: *Annual Institute of Lake Superior Geology Proceedings and Abstracts*, v. 34, pt. 1, p. 40-41.
- Larue, D.K., 1983, Early Proterozoic tectonics of the Lake Superior region: Tectonostratigraphic terranes near the purported suture zone: *Geological Society of America Memoir* 160, p. 33-47.
- Pearce, J.A., and Norry, M.J., 1979, Petrogenetic implications of Ti, Sr, Y and Nb variations in volcanic rocks: *Contributions to Mineralogy and Petrology*, v. 69, p. 33-47.
- Sun, S.S., and Nesbitt, R.W., 1978, Geochemical regularities and genetic significance of ophiolitic basalts: *Geology*, v. 6, p. 689-693.
- Ueng, W.C., Fox, T.P., Larue, D.K., and Wilband, J.T., 1988, Geochemistry and petrogenesis of the Early Proterozoic Hemlock volcanic rocks and the Kiernan Sills, southern Lake Superior region: *Canadian Journal of Earth Science*, v. 25, p. 528-546.
- Van Schmus, W.R., 1976, Early and Middle Proterozoic history of the Great Lake area, North America: *Philosophical Transactions of Royal Society of London, Series A*, v. 280, p. 605-628.
- Wee, S.M., 1989, *Geochemical investigation of Early Proterozoic igneous rock in northern Michigan and the northeast portion of Wisconsin, U.S.A.*: Ph.D. thesis, East Lansing, MI, Michigan State University, 185 p.

Crustal structure of northeastern Lake Superior  
from GLIMPCE reflection and refraction data

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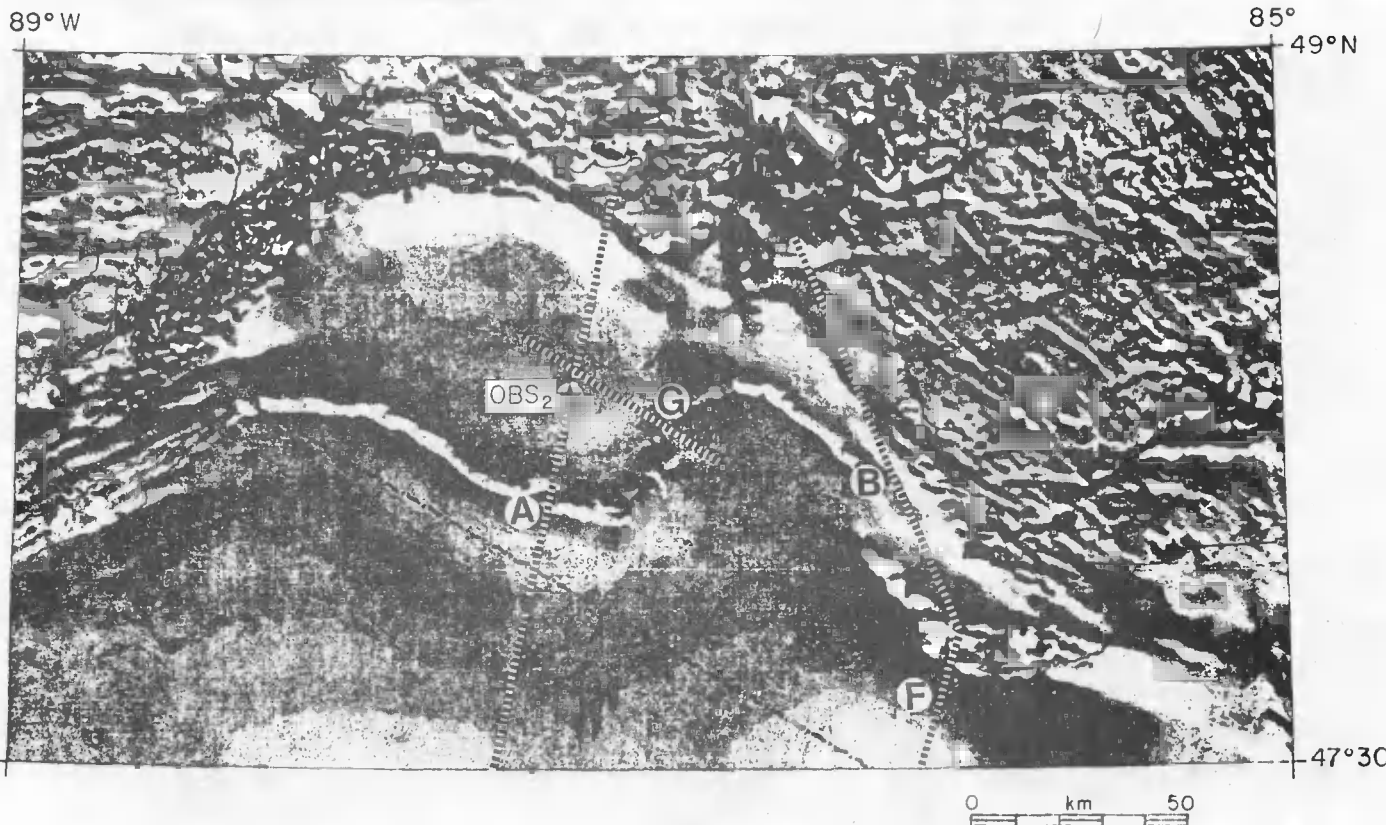
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The deep structure of the Midcontinent Rift beneath Lake Superior was imaged in detail during the GLIMPCE reflection survey of the Great Lakes. Reflection profiles across the rift revealed a deep asymmetric central graben [Behrendt et al., 1988; Cannon et al., 1989; Green et al., 1989] whose existence and magnitude was not documented before. The geometry of the central graben changes significantly along the axis of the Midcontinent Rift System and a sequence of volcanic and sedimentary rocks, in places greater than 30 km thick, fills the graben. Here we present additional GLIMPCE seismic reflection sections, refraction and stacking velocity analyses, and potential field data from outside the main rift basin beneath northeastern Lake Superior.

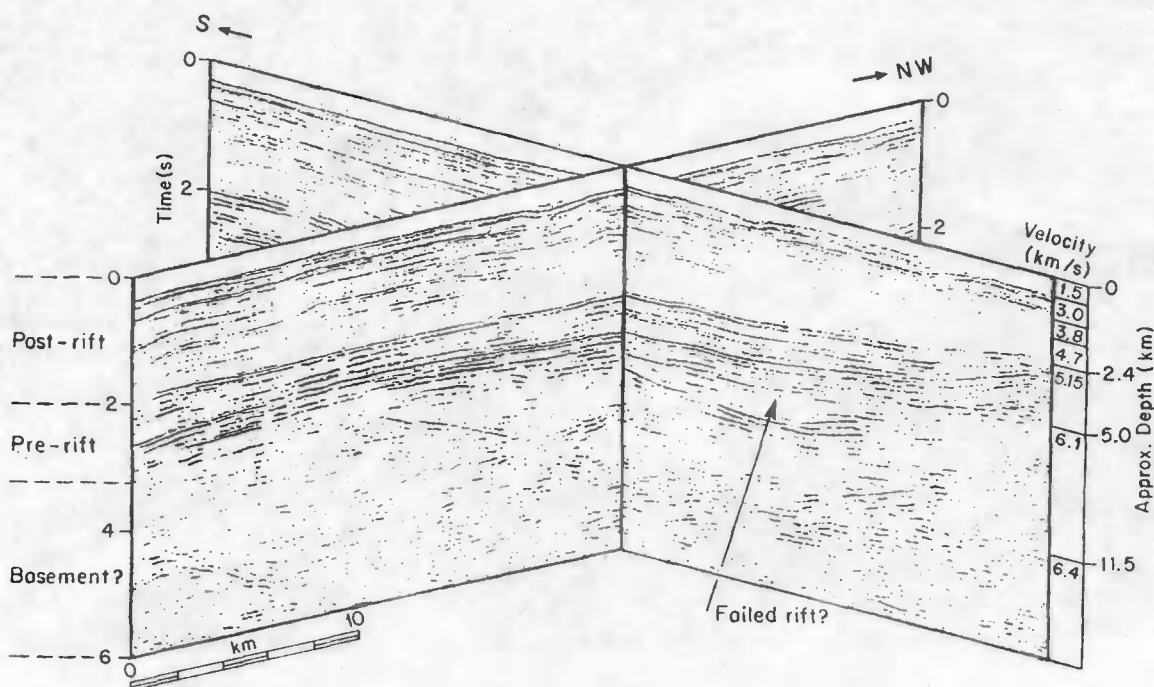
Figure 1. GLIMPCE reflection profiles (A, B, F and G) and OBS recording site on shaded relief magnetic anomaly map.



These data will shed some light on (a) pre-Keweenaw structures (aulacogens ?), (b) correlations among Keweenaw rocks (based on seismic velocities), (c) thickness and areal extent of pre- and post-rift sediments, and (d) the correlation between potential field data and seismic structures.

The Location of GLIMPCE reflection profiles (A, B, F and G) and one of the ocean bottom seismometers (OBS) are shown on a shaded relief magnetic anomaly map in Figure 1. At the intersection of profiles A and G we have obtained a high quality image of the upper crust that has some 3-D control. Figure 2 shows a shallow, fault-bounded graben structure preserved beneath early Keweenaw sediments and volcanics [Osler volcanics in the interpretation by Cannon et al., 1989]. This seismic image supports a tectonic model of lower Proterozoic intracratonic rifting prior to the advent of Keweenaw volcanic units and suggests that pre-Keweenaw rocks (i.e. the Sibley Group) were deposited in a shallow, probably fault-bounded intracratonic basin. The reflective, layered Lower Keweenaw sequence, found on all profiles in northeastern Lake Superior, can be used as a marker horizon to define the lateral extent of early Keweenaw volcanic activity outside the main rift basin.

**Figure 2.** Migrated reflection profiles along lines A and G showing subsurface structure beneath northeastern Lake Superior with (from the top) non-reflective post-rift sediments, reflective Early Keweenaw volcanic unit, and an interpreted image of a Lower Proterozoic fault-bounded rift (aulacogen). Generalized velocity-depth profile was determined from OBS wide angle recording along line A.



The wide-angle wavefields recorded by OBS [GLIMPCE seismic refraction working group, 1989] and the 120-channel reflection seismic recording system have been used to define the shallow velocity structure. The velocity model has provided useful information for structural interpretations of complex reflection sections. Volcanics and sediments of Keweenawan age outcrop extensively in the southern and western Lake Superior region. On contrast, no post-rift sediments outcrop in the northeastern Lake Superior region. Earlier studies [Halls and West, 1971] presented evidence that Lake Superior is underlain by as much as 3 km thick post-rift sediments. The GLIMPCE experiment confirms their interpretation and suggests an even wider areal extension of low velocities appropriate for upper Keweenawan (Bayfield-Jacobsville equivalent) sandstones than previously thought; it also indicates an apparent lack of thick unconsolidated sediments (glacial drift) in northeastern Lake Superior. Findings of the seismic studies such as (a) the lateral extension of Early Keweenawan volcanics, (b) the lateral extension of low velocity post-rift sediments, and (c) the position of late intrusive complexes along the basin bounding faults and accommodation zones can be correlated with major trends and breaks in the gravity and magnetic anomaly patterns.

#### References

- Behrendt, J.C., A.G. Green, W.F. Cannon, D.R. Hutchinson, M.W. Lee, B. Milkereit, W.F. Agena, and C. Spencer. Crustal structure of the Mid-continent Rift system - Results from GLIMPCE deep seismic reflection profiles, *Geology*, 16, 81 - 85, 1988.
- Cannon, W.F., A.G. Green, D.R. Hutchinson, M.W. Lee, B. Milkereit, J.C. Behrendt, H.C. Halls, J.C. Green, A.B. Dickas, G.B. Morey, R. Sutcliffe and C. Spencer, The North American Midcontinent Rift beneath Lake Superior from GLIMPCE seismic reflection profiling, *Tectonics*, 8, 305 - 332, 1989.
- Green, A.G., W.F. Cannon, B. Milkereit, D.R. Hutchinson, A. Davidson, J.C. Behrendt, C. Spencer, M.W. Lee, P. Morel-à-l'Huissier and W.F. Agena, A "GLIMPCE" of the deep crust beneath the Great Lakes, in: *Properties and Processes of the Earth's Lower Crust*, R.F. Mereu, S. Mueller, D.M. Fountain (Eds.), Geophysical Monograph Series, 51, 65 - 80, 1989.
- GLIMPCE Seismic Refraction Working Group, GLIMPCE seismic experiments - long-offset recordings, *EOS*, 70, 841 - 853, 1989.
- Halls, H.C., and G.F. West, A seismic refraction survey in Lake Superior, *Canadian Journal of Earth Sciences*, 8, 610 - 630, 1971.

## THE SONJU LAKE INTRUSION AND ASSOCIATED KEWEENAWAN ROCKS: GEOCHEMICAL AND GEOPHYSICAL EVIDENCE OF PETROGENETIC RELATIONSHIPS

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The Sonju Lake intrusion (SLI) is a layered sequence of mafic cumulates that is one of the most completely differentiated bodies known in the Keweenawan section (Weiblen, 1982). It is part of the Beaver Bay Complex - a multiple intrusive supersuite of gabbroic to granitic rocks which were emplaced into volcanic rocks of the North Shore Volcanic Group near Silver Bay and Finland in northeastern Minnesota (Fig. 1). Preliminary geochemical data and somewhat equivocal intrusive relationships between the SLI and spatially associated diabasic and ferrogabbroic rocks led Miller (1989) to suggest that all of these intrusive units may be comagmatic and roughly coeval. Also, chemical data of Rogge (1989) can be interpreted to indicate that the extensive mass of granitic to granodioritic rocks that overlie the SLI are siliceous differentiates of the layered sequence. However, the results of geochemical and geophysical modelling, together with further mapping and petrographic studies, indicate that the SLI is genetically and temporally distinct from these other units of the Beaver Bay Complex.

The laminated and locally layered, mafic cumulates of the SLI, first described in detail by Stevenson (1974), occur as a gently ( $15^{\circ}$ - $25^{\circ}$ ) southward-dipping sequence which has a stratigraphic thickness of about 1100 meters, assuming negligible faulting (Figs. 1 & 2). The footwall of the intrusion is composed of a complex mixture of gabbro, granophyre, and volcanic hornfels. The uppermost laminated ferrodioritic cumulates are overlain by a massive granophyric olivine ferrodiorite that irregularly grades into a prismatic mafic granodiorite over a stratigraphic thickness of about 100 meters. Farther south (200-400 m upsection?), this prismatic granodiorite grades into a leucocratic granophyric granite. The granodiorite and granite are collectively termed the Finland granite (Fig. 1). The eastern margin of the SLI is abruptly truncated by a NNE-trending fault that juxtaposes the SLI and olivine gabbroic rocks of the Beaver River diabase. The aeromagnetic signature of the SLI, which can be traced to the west beneath a cover of glacial till, indicates that the intrusion curves to the south, rimming the underside of the Finland granite (Fig. 1). The SLI has a half-saucer shape with a strike length of at least 20 kilometers.

The Beaver River diabase is typically a fine- to medium-grained ophitic olivine diabase occurring in dikes and sills throughout the Beaver Bay Complex (Fig. 1). Emplaced into the Beaver River diabase in scattered locations are the typically zoned bodies of ferrogabbroic rocks termed the Silver Bay intrusions. Geochemical modelling by Shank (1990) suggested that the Silver Bay intrusions represent a more fractionated derivative of the original Beaver River diabase magma. Intrusive relationships and a compositional hiatus between these rock units imply, however, that this fractionation must have occurred in a deeper magma chamber. These conclusions and the general compositional similarities of the Silver Bay intrusions and the upper cumulates of the SLI led Miller (1989) to speculate that the SLI represented such a chamber, and if so, that the Beaver River diabase possibly was parental to the layered cumulates of the SLI.

Additional mapping along the eastern margin of the SLI now indicates that the truncation of the intrusion is due largely to the emplacement of a large dike of Beaver River diabase (Fig. 1). Two large inclusions of the SLI have been found in the diabase. Although a postmagmatic fault also exists between the SLI and the diabase, it is small scale relative to the steep fault that accommodated the diabase. The latter had east side-down displacement of perhaps as much as 1.5 km.

Further evidence against the Beaver River diabase or a similar magma composition having been parental to the SLI is given by the distinct composition of an estimated parent magma for the intrusion. A weighted sum of over 20 whole rock analyses through a stratigraphic section of the SLI (Fig. 2) defines a bulk composition that is overall more evolved than average Beaver River diabase (Table 1). The plausibility of this estimated parent composition, which is very similar to that calculated by Stevenson (1974), is verified in two ways.

1) The most primitive olivine ( $Fo_{79.5}$ ) at the base of the intrusion is exactly that which should initially crystallize from the estimated parent magma. Based on an olivine-liquid  $K_D^{(Fe-Mg)}$  of 0.3

(Roeder & Emslie, 1970), the calculated mg# ( $\text{Mg}/\text{Mg}+\text{Fe}$ ) of 53.9-55.3 should produce cumulus olivine with a composition of Fo<sub>79.6-80.5</sub>.

2) The crystallization sequence observed in the SLI (Fig. 2), namely Ol - Ol+Pl - Ol+Pl+Cpx - Ol+Pl+Cpx+Feox, is identical to that predicted when the estimated parent composition is applied to a low pressure fractional crystallization model (Neilsen, 1988). In contrast, plagioclase is apparently the first phase to crystallize from a Beaver River diabase composition when its average composition is applied to the same model. A liquid line of descent calculated for the SLI (by summing all rocks above a particular level) also fits that predicted by fractional crystallization modelling of the estimated parent magma, if a system open to some periodic recharge is assumed.

The composition of the granodioritic to granitic rocks which overlie the layered cumulates correspond very well to that which would be expected for a siliceous differentiate of the SLI (Rogge, 1989). About 7% (by weight) of olivine Fe-granodiorite, which directly overlies the layered cumulates, is included in the estimated SLI parent composition (Table 1). However, the amount of additional granodioritic to granitic material that may be included in the bulk composition is constrained to less than 5% of the total. More than this will drop the mg# of the bulk composition to less than what could have crystallized the Fo<sub>79</sub> olivine at the base of the intrusion. Based on the relative map areas, the volume of felsic material appears to be much too great relative to the amount of mafic material to have been derived from SLI differentiation.

To test whether this apparent disproportion of felsic to mafic material is evident in the third dimension, gravity and aeromagnetic data were modelled along a traverse over the SLI and Finland granite (Line A, Fig. 1). If the SLI is assumed to be at least 1 km thick beneath the Finland granite, the magnetic and gravity models constrain the granite and granodioritic material to extend to a depth of at least 1.5 km at its thickest point, adjacent to the fault/diabase along its SE margin (Fig. 1). A best fit of the gravity and magnetic data for such a volume of felsic material is produced with relative proportions of mafic to felsic material of about 1:1 and thereby indicates that the granitic rocks are not upper differentiates of the SLI.

In conclusion, the SLI is temporally and genetically distinct from other bodies currently known to comprise the Beaver Bay Complex. It was emplaced beneath a cap of the granitic to granodioritic rocks of the Finland granite. (Because these felsic rocks are compositionally similar to what a siliceous differentiate of the SLI would be, the amount of assimilation is difficult to estimate. Perhaps isotopic data may reveal the extent of assimilation.) The differentiated body which provides the genetic link between the evolved Silver Bay intrusions and the Beaver River diabase is not the older SLI and remains unknown.

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- Miller, J.D., Jr., 1988, Geologic map of the Silver Bay and Split Rock Point NE quadrangles, Lake County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-65.
- Miller, J.D., Jr., 1989, Geology of the Beaver Bay Complex, northeastern Minnesota. *Inst. on Lake Superior Geology*, 35th, Duluth, Minnesota, p. 56-58.
- Neilsen, R.L., 1988, TRACE.FOR: A program for the calculation of combined major and trace element liquid lines of descent for natural magmatic systems: *Computers & Geosciences*, v. 14, p. 15-35.
- Roeder, P.L. and Emslie, R.F., 1970, Olivine-liquid equilibria: *Contributions to Mineralogy and Petrology*, v. 29, p. 275-289.
- Rogge, M.K., 1989, Geochemistry of the Sonju Lake layered mafic intrusion: Unpub. M.S. thesis, Iowa State University, 92 p.
- Shank, S.G., 1990, The petrology of the Beaver Bay Complex near Silver Bay, northeastern Minnesota: Unpub. M.S. thesis, University of Minnesota, Minneapolis, 130 p.
- Stevenson, R.J., 1974, A mafic layered intrusion of Keweenawan age near Finland, Lake County, Minnesota Unpub. M.S. thesis, University of Minnesota, Minneapolis, 160 p.
- Weiblen, P.W., 1982, Keweenawan intrusive igneous rocks, in Wold, R.J., and Hinze, W.J., eds., *Geology and tectonics of the Lake Superior Basin: Geol. Soc. America Memoir 156*, p. 57-82.

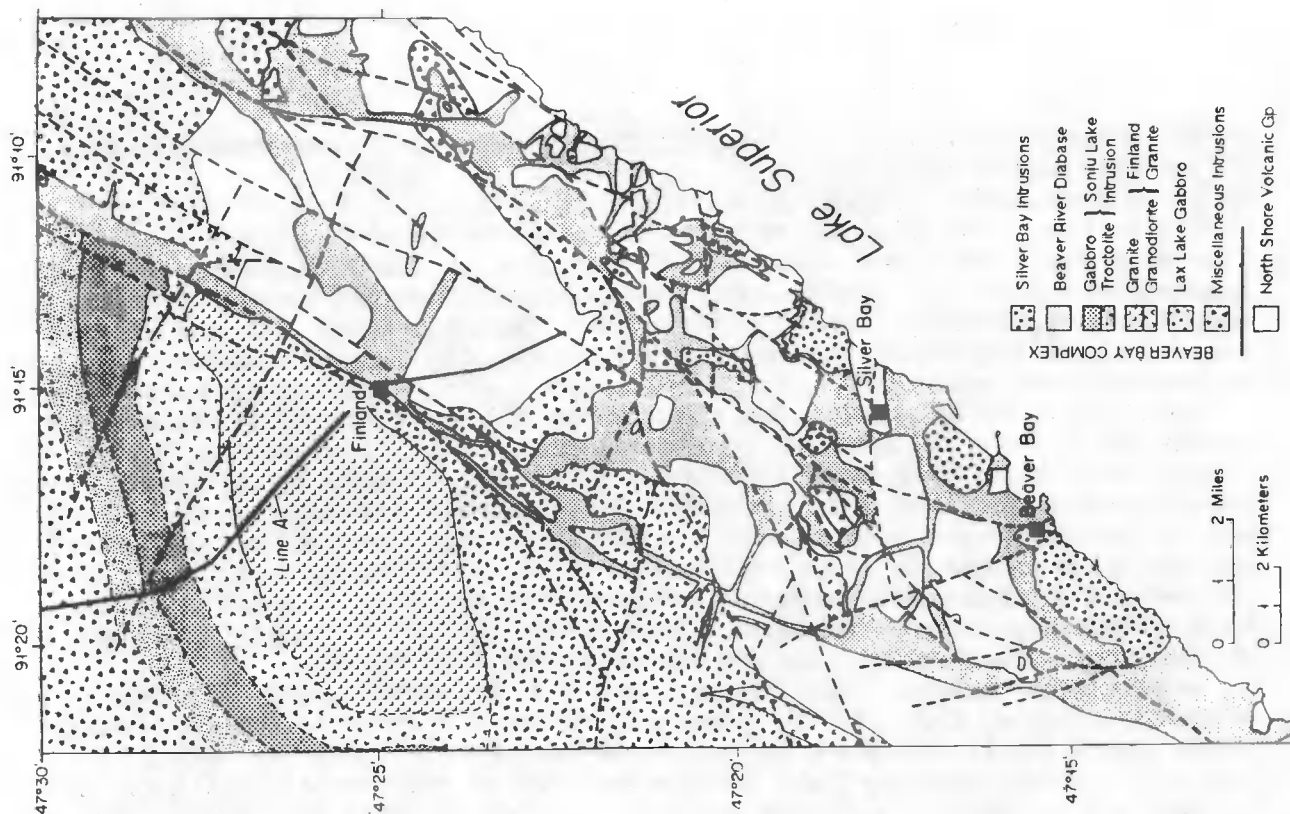


FIGURE 1. Generalized geology of the Beaver Bay Complex in the vicinity of Silver Bay and Finland, Minnesota. Line A traces the gravity and magnetic profile. Geology shown in the northern half of the map is a preliminary compilation.

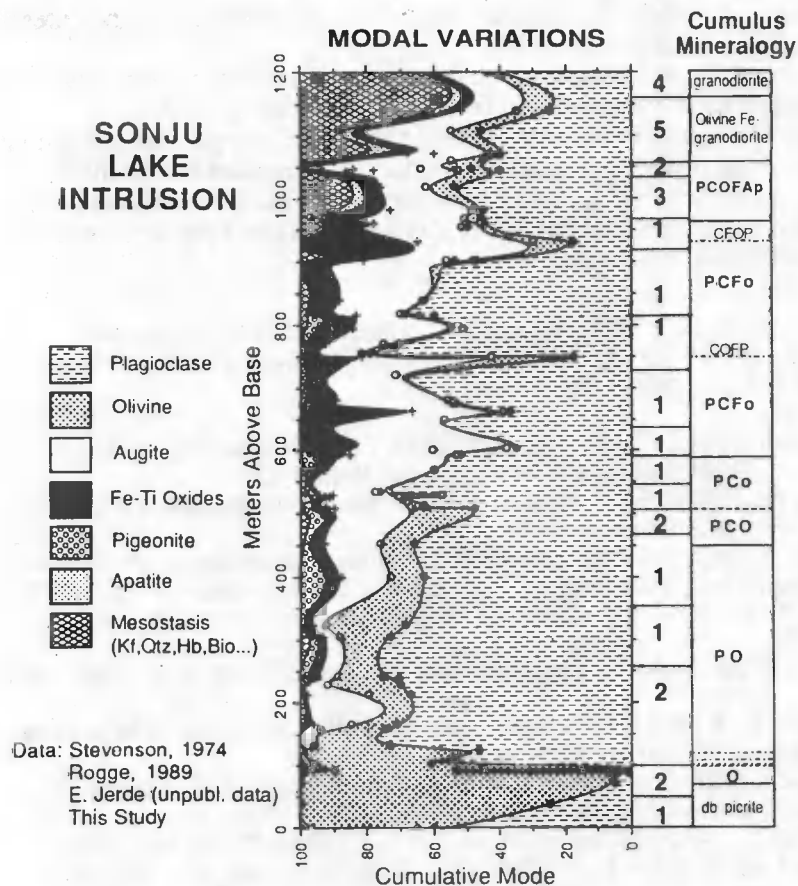


FIGURE 2. Stratigraphic profile of the Sonju Lake intrusion showing modal variations, cumulus mineralogy, and composition intervals summed to determine the bulk composition of the intrusion (Table 1, SLI Parent). Number of whole rock analyses averaged to represent the composition of each interval is noted.

TABLE 1. Compositions of SLI parent magma and average Beaver River diabase

|                                | SLI Parent | BRD    |
|--------------------------------|------------|--------|
| SiO <sub>2</sub>               | 47.8       | 48.3   |
| TiO <sub>2</sub>               | 2.06       | 1.39   |
| Al <sub>2</sub> O <sub>3</sub> | 14.8       | 16.1   |
| FeO <sup>1</sup>               | 13.4       | 13.2   |
| MnO                            | 0.19       | 0.17   |
| MgO                            | 7.90       | 8.11   |
| CaO                            | 9.5        | 10.5   |
| Na <sub>2</sub> O              | 2.61       | 2.27   |
| K <sub>2</sub> O               | 0.55       | 0.33   |
| P <sub>2</sub> O <sub>5</sub>  | 0.30       | 0.14   |
| TOTAL                          | 99.04      | 100.45 |
| mg#(.85FeO)                    | 55.34      | 56.33  |
| mg#(.9FeO)                     | 53.92      | 54.92  |
| Sc                             | 33         | 28     |
| Cr                             | 120        | 167    |
| Co                             | 59         | 61     |
| Ni                             | 165        | 190    |
| Rb                             | 18         | 9      |
| Sr                             | 271        | 227    |
| Ba                             | 161        | 143    |
| Y                              | 17.6       | 20.0   |
| Zr                             | 103        | 87     |
| Nb                             | 7          | 23     |
| Hf                             | 2.9        | 2.8    |
| Ta                             | 0.6        | 0.7    |
| U                              | 0.8        | 0.5    |
| Th                             | 1.5        | 1.1    |
| La                             | 12.4       | 11.2   |
| Ce                             | 30.2       | 26.1   |
| Sm                             | 4.4        | 3.7    |
| Eu                             | 1.6        | 1.3    |
| Tb                             | 1.1        | 0.7    |
| Yb                             | 2.2        | 2.3    |
| Lu                             | 0.34       | 0.32   |

## MESOSCOPIC EVIDENCE FOR B<sub>1</sub> DEFORMATION IN LOWER PROTEROZOIC SUPRACRUSTAL ROCKS NEAR ROCHFORD, SOUTH DAKOTA.

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### Introduction

The Rochford mining district is located in the Precambrian core of the Black Hills Uplift, approximately 25 miles (40 km) west of Rapid City, South Dakota (Figure 1A). Highly deformed lower Proterozoic rocks underlie most of the area and include slate, phyllite, and schist intercalated with metavolcanics, metagabbro, metachert, and various facies of meta-iron formation (Dewitt and others, 1986). Previous work in the area includes several recent M.S. theses and an extensive mapping effort by the U.S.G.S. in the late 1960's, which culminated with the publication of the first comprehensive geologic map of the district by Richard Bayley in 1972. Structural interpretations thus far have been based primarily on a preferred stratigraphic sequence which was originally proposed by Bayley (1972), based on correlations with a key unit in the Lead district to the north (Ellison Formation at Lead correlated with the Moonshine Gulch Quartzite at Rochford) and also on two available age dates of intercalated volcanoclastic units within the two areas. The present study involved detailed structural/lithologic mapping of an area about 2 miles southwest of the town of Rochford, located in Pennington County, South Dakota. Our objective was to delineate the nature of major structural features within the map area. To accomplish this task, the cornerstone of our field technique involved using fold overprinting relationships to classify and map mesoscopic fabric elements. In addition, detailed lithologic mapping was carried out utilizing a distinctive biotite-garnet phyllite unit as a structural marker horizon.

### Descriptive structural geology

Style group B<sub>1</sub> is defined by the macroscopic outcrop pattern of the biotite-garnet phyllite unit and by mesoscopic B<sub>1</sub> folds observed at three key localities within the field area. B<sub>1</sub> folds observed in outcrop and also on the macroscopic scale are tight to isoclinal. Structural analysis of B<sub>1</sub> folds on a mesoscopic scale is impossible, since very few first generation fabric elements were preserved in the field area. However, based on the predominant southeasterly plunge of L<sub>2</sub> bedding-cleavage intersection lineations, the first system of folds may have trended east-west, with steeply south-dipping axial surfaces.

Style group  $B_2$  folds re-fold older  $B_1$  structures or bedding ( $S_0$ ) and are observable on both the macroscopic and mesoscopic scales.  $B_2$  folds are open to tight, with a pervasive axial plane foliation ( $S_2$ ) defined by parallel preferred-orientation of mica particles. The  $S_2$  foliation strikes northwest and dips steeply to the northeast and is the dominant structural fabric throughout the Rochford district. Both  $B_2$  fold axes and  $L_2$  cleavage-bedding intersection lineations plunge to the southeast.

Third generation ( $B_3$ ) structures are present throughout the field area and consist of moderately to strongly developed crenulations on  $S_2$  cleavage surfaces. Elements associated with style group  $B_3$  are the  $S_3$  crenulation cleavage and the  $L_3$  crenulation lineation.  $S_3$  planes strike to the northeast and dip to the south, whereas the  $L_3$  wrinkle

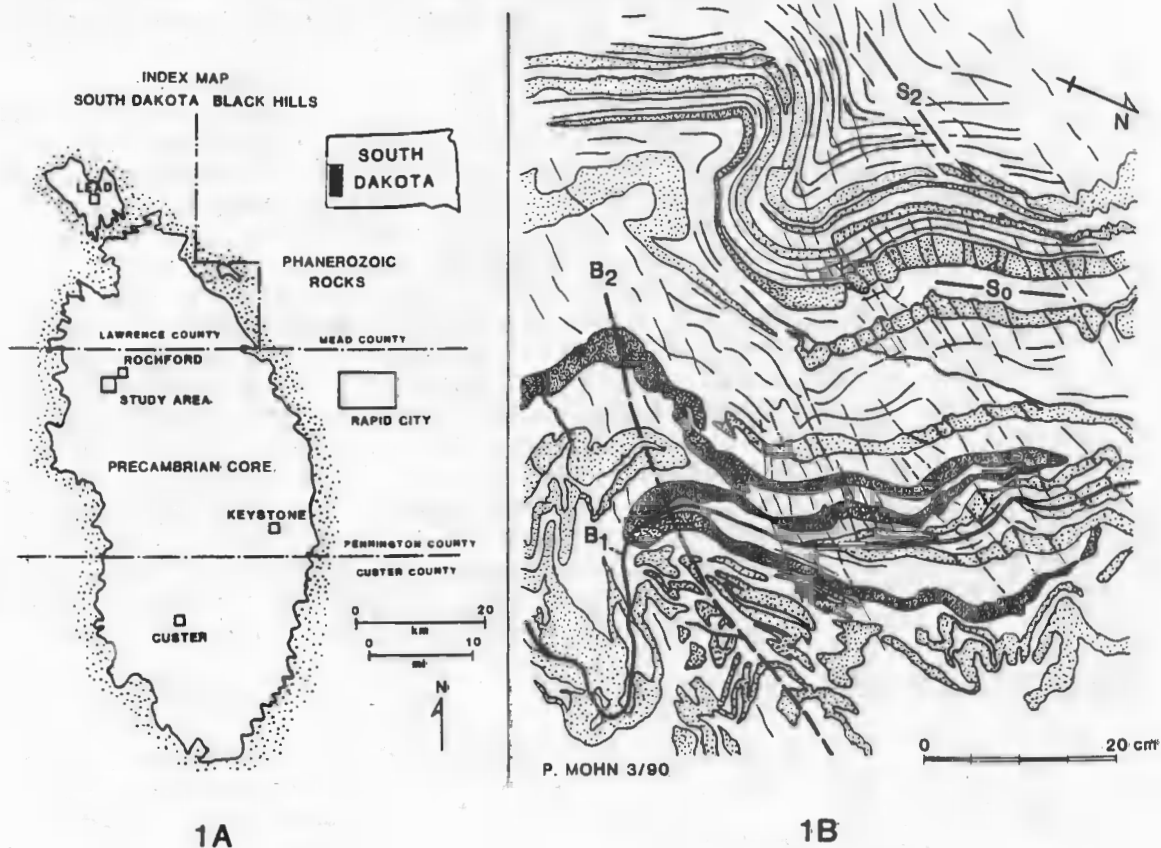


Figure 1

Index map of the South Dakota Black Hills (1A), and a sketch of fold overprinting relationships (1B) as observed on the back of a mine adit located in the southern part of the field area. Heavy stippled pattern shows a  $B_1$  isoclinally folded chert bed refolded by  $B_2$ , with the resulting type III interference pattern. The sketch is a pen and ink tracing of a photograph.

lineation plunges to the southeast, roughly parallel to  $L_2$  lineations. With the exception of local reversals of the plunge direction of  $L_2, B_3$  deformation had little effect on the orientation of major structures within the map area.

### Conclusions

The results of our detailed work show, at least within the confines of the map area, that there is a reversal of the stratigraphic rock sequence proposed by Bayley (1972) for the area on the western edge of the Rochford anticlinorium, where the present study was undertaken. Secondly, distinctive first generation ( $B_1$ ) folds were observed both on the mesoscopic scale and on the macroscopic scale, which is defined by the outcrop pattern of the biotite-garnet phyllite marker horizon. Type III interference patterns were produced as a result of overprinting by a later fold generation ( $B_2$ ) which was non-coaxial to the first-generation  $B_1$  folds (Figure 1B). A third phase of folding is evident based on the presence of a locally well-developed crenulation cleavage ( $S_3$ ). This crenulation cleavage overprints  $B_2$  mesostructures in the study area.

To the best of our knowledge, the delineation of first generation ( $B_1$ ) structures and the distinctive structural overprinting relationships observed in the map area are the first such examples documented in the Rochford district. The structural relationships we propose for the map area are in general agreement with those proposed by Redden and French (1989) for the central Black Hills near Mystic, thereby indicating that similar techniques of structural/lithologic mapping may be successfully applied to other areas in the Precambrian terrane of the Black Hills.

### References

- Bayley, R.W., 1972 A preliminary report on the geology and gold deposits of the Rochford district, Black Hills, South Dakota: U.S.G.S. Bull. 1332-A.
- Dewitt, E., J.A. Redden, A.B. Wilson and David Buscher, 1986 Mineral resource potential and geology of the Black Hills National Forest, South Dakota and Wyoming: U.S.G.S. Bull. 1580.
- Redden, J.A. and G.M. French, 1989 Geologic setting and potential exploration guides for gold deposits, Black Hills, South Dakota: in United States Gold Terranes, Part I, U.S.G.S. Bull. 1857-B; D.R. Shawe, R.P. Ashley, and L.M.H. Carter, eds.

THE PHYSICAL VOLCANOLOGY AND HYDROTHERMAL ALTERATION  
ASSOCIATED WITH THE MASSIVE SULPHIDE DEPOSITS OF THE  
SOUTH STURGEON LAKE AREA, NORTHWESTERN ONTARIO

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The south Sturgeon Lake area of northwestern Ontario is underlain by a well preserved Archean submarine caldera which is approximately 30 Km in strike length. Within the caldera five ash flow tuff units have been recognized, and these range from 100 to more than 1200 meters in stratigraphic thickness. The ash flow units vary from massive and pumice-rich to bedded. Commonly, quartz crystal-, pumice-rich basal units are overlain and separated by well bedded ash units. The five known massive sulphide deposits (Mattabi, F-Group, Sturgeon Lake, Lyon Lake, and Creek Zone) occur within the caldera and are hosted by the ash flow tuff deposits.

Associated with the ash flow tuffs are coarse heterolithic breccias which contain clasts that are composed dominantly of precaldern lithologies. The breccias underlie, and locally, are interlayered with, the ash flow tuffs. The breccias vary from 100 to more than 750 meters in thickness. Clasts in the breccia vary from lapilli-sized to large blocks at least 100 meters in diameter.

The five ash flow units indicate five separate periods of explosive, silicic volcanism accompanied by caldera collapse; the breccias represent mesobreccia deposits formed from material which slumped into the caldera during and after each caldera collapse episode occurred.

Ore forming hydrothermal activity was associated with at least four of these eruptive episodes. Early, regional carbonatization of the rocks is cross-cut by alteration assemblages containing: a) iron carbonate  $\pm$  iron chlorite; b) chloritoid  $\pm$  iron carbonate and/or iron chlorite; c) aluminum silicates (pyrophyllite, andalusite, and/or kyanite) + chloritoid; and d) aluminum silicates. Aluminum silicate alteration zones are dominantly confined to the synvolcanic faults that acted as conduits for the metalliferous, ore-forming hydrothermal fluids. These zones lead up to the massive sulphide deposits, which are, in turn, surrounded by semiconformable zones of aluminum silicate, aluminum silicate + chloritoid, and chloritoid alteration.

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## TECTONIC RAMIFICATIONS OF GNI/ARGONNE LAKE SUPERIOR SEISMIC DATA

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### ABSTRACT

Geologic analysis of Grant-Norpac Inc. (GNI)/Argonne reflection seismic lines in western Lake Superior requires revision of Middle Proterozoic Keweenaw stratigraphy, tectonics and basin evolution. The seismic diagrams were previously presented as a poster session at the Duluth 1989 ILSG Annual meeting.

The Isle Royale Fault is not continuous with the Douglas Fault. No vertical or high-angle reverse fault with displacement more than 0.2 seconds of two-way travel time, roughly equivalent to 500 m, is seen to cross Grant-Norpac/Argonne Line-08. If there is a fault, it does not express itself as high-angle, but it could be a thrust fault, and as such is not evident in the seismic data.

The Bayfield Group rests with strong, regional angular unconformity on the Oronto Group, which has lost up to one-half its thickness as a result of erosion prior to deposition of the Bayfield Group.

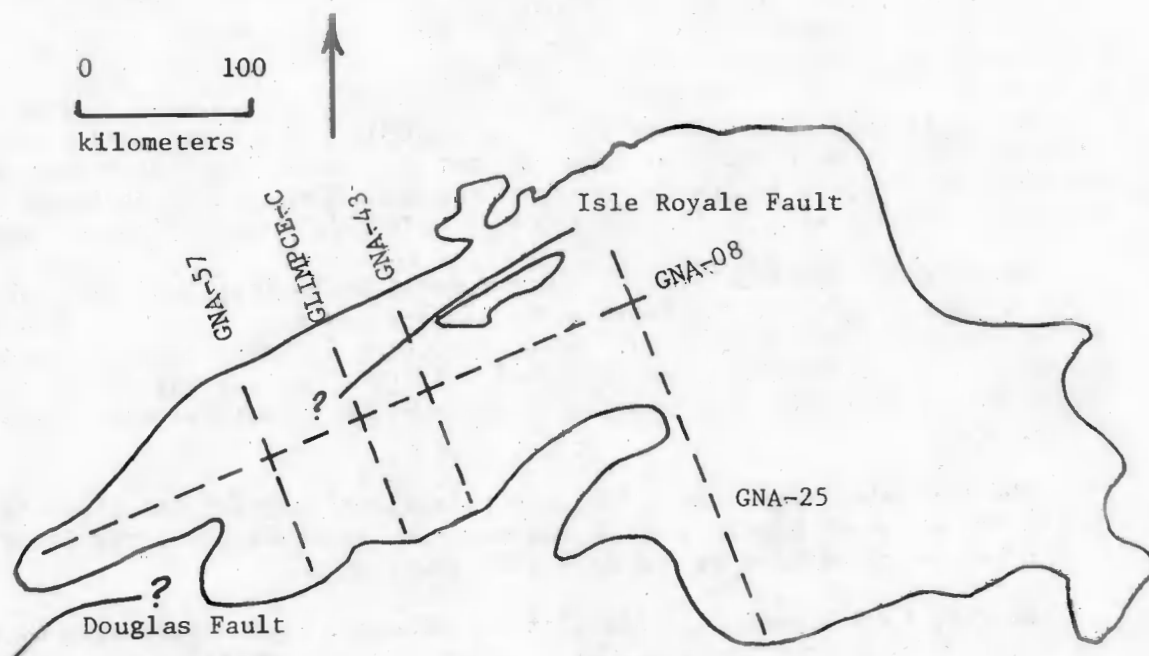
Western Lake Superior consists of two distinct basins separated by an Archean-cored ridge (the locus of GLIMPCE Line-C). The western volcanic/sedimentary basin is herein named the Claude Jean Allouez Basin (informally referred to as the Allouez Basin); the eastern basin, the Jacques Marquette Basin (informally referred to as the Marquette Basin); and the intervening ridge, the Walter White Ridge (informally referred to as the White Ridge). Each basin consists of multiple volcanic successions overlain by a transgressive Oronto sequence which filled the two basins, and ultimately covered the White Ridge. The Oronto in turn is unconformably overlain by the Bayfield Group. Seismic cross lines define stratigraphic relations. Seismic form lines in the Portage Lake Volcanic Group suggests abundant intra-formation sedimentary units, and supports continuity of the Greenstone Flow from Isle Royale to the Keweenaw Peninsula. It may be possible to define the lateral extent of the Oak Bluff Formation (formerly the unnamed formation of Johnson and White, 1969).

These relationships strongly support a fundamental, rift-unit framework of isolated basins separated by syndepositional accommodation structures. The Walter White Ridge is the first direct evidence of accommodation structures being associated with the Midcontinent Rift System.

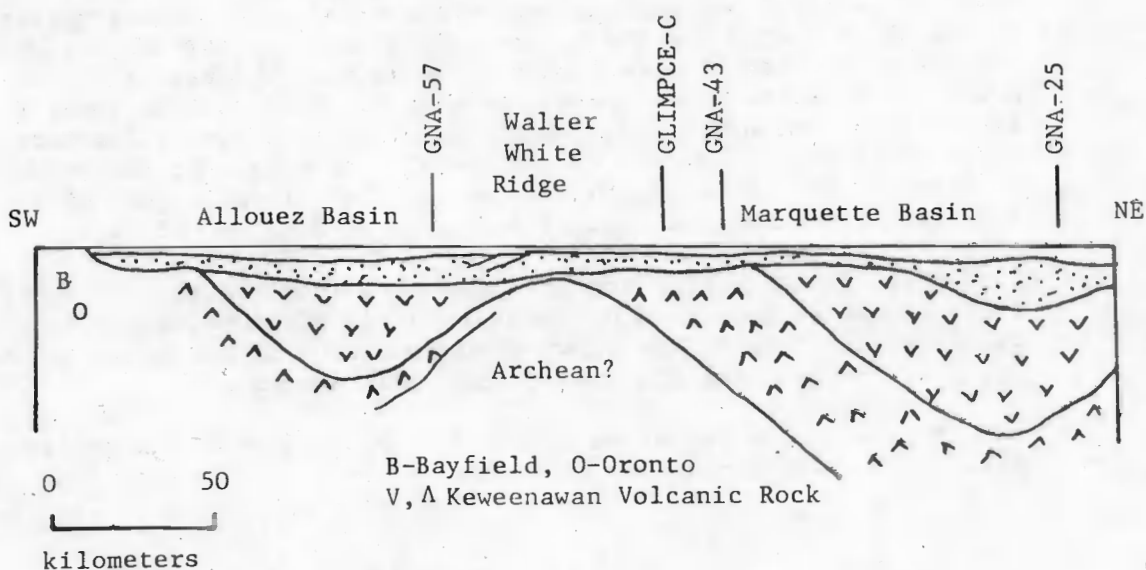
This work was supported by the U.S. Department of Energy, Office of Energy Research, under Contract W-31-109-ENG-38.

Reference cited:

Johnson, R.F., and White, W.S., 1969, Preliminary report on the bedrock geology and copper deposits of the Matchwood quadrangle, Ontonagon County, Michigan: U.S. Geological Survey open-file report, 31 p.



Location of seismic profiles and Isle Royale and Douglas Faults



Interpretation of GNA-08 (prepared by A. Dickas and M. Mudrey, 1989)

## **Constraints on Archean versus Proterozoic deformation in Archean Rocks of the Negaunee area, Upper Michigan**

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The Negaunee area of Michigan's upper Peninsula contains deformed Archean greenstones and metasediments of the Northern Complex as well as Proterozoic metasediments along the northern margin of the Marquette syncline and the southeastern end of the Dead River Basin. Although the Proterozoic rocks of the area were obviously deformed during the Penokean Orogeny, the effects of this event on the adjacent Archean rocks are unclear. The regional foliation trends in both the Archean and Proterozoic rocks are subparallel (vertical, striking ca. N. 70° W.), and the principle axes of finite strain measured in previous studies (Carter, 1989 and Westjohn, 1978) are also nearly parallel in the Archean and Proterozoic rocks.

We have analyzed deformation fabrics and finite strains ( $R_f/\phi$  technique) from Archean rocks of the Kitchi Schist and the Mona Schist in an effort to evaluate: (1) the deformation sequence in the Archean rocks, and (2) the degree to which Proterozoic deformation has effected the Archean rocks. As a local standard of comparison, we have analyzed the geometry of Proterozoic folding in the Goodrich Quartzite and lower units of the Michigamme Formation along the southeastern margin of the Dead River Basin. Our analysis indicates that Proterozoic deformation did not effect Archean rocks in a ductile fashion.

The oldest Archean deformation generated an L to LS fabric with a steeply plunging linear axis in the Kitchi Schist south of the Dead River Basin. The planar aspect of the fabric defines a locally well developed vertical foliation striking N. 70° W. that is prominent in the clastic units of both the Kitchi Schist and especially the Mona Schist throughout the region (Figure 1A). Finite strains that we believe were generated primarily as a result of this deformation were measured in the agglomerates of the Kitchi Schist and show slightly prolate strain ellipsoids with the maximum (X), intermediate (Y), and minimum (Z) principle axes vertical, E-W, and N-S, respectively (Figure 2A and 3). Strain analyses from the Kitchi Schist and the adjacent Mona Schist (Carter, 1989), and the dominant N. 70° W. foliation are consistent with N- to NNE-directed shortening during this event. Sparse folds with E-W trending axial planes occur in the Nealy Creek (NC) and sheared rhyolite tuff (srt) members of the Mona Schist north of the Dead River Basin where the dominant foliation orientation is roughly E-W. These folds have variable hinge-line orientations that plunge shallowly to moderately east and west. Stretching lineations in these same rocks show a similar distribution, also plunging to both the east and west. We believe that these lineations and the sparse folds may have been reoriented during a second period of deformation that is variably partitioned into the NC and srt members of the Mona Schist.

The second deformation produced a set of conjugate crenulation cleavages that are locally developed in the highly foliated NC and srt members of the Mona Schist. Although some of the crenulations occur in an area mapped as a broad zone of shear, they also occur several kilometers outside of this zone in parts of the NC member that are not sheared. Crenulations with axial planes that strike NNW-SSE have "S" asymmetry while those with axial planes that strike roughly E-W have "Z" asymmetry (Figure 1B). The concomitant generation of these orientations requires that the greatest principle stress be at a low angle to the earlier foliation planes and coincident with the bisector of the angle between the conjugate cleavage planes (Cosgrove, 1976); only a NW-directed compression is consistent with this geometry. Strain analyses of crenulated samples from the srt member are also consistent with NW-SE

directed shortening. In these samples, the XY principle plane of the finite strain ellipsoid is steeply dipping, NE-striking, and normal to the direction of shortening estimated from crenulation axial planes (Figure 2B). We believe this second deformation is also of Archean age, because NW-directed compression is not observed in the Proterozoic rocks of the region.

For instance, regional folding of the Proterozoic Goodrich Quartzite and the lower part of the Michigamme Formation is about a N. 70° W. axial plane (Figure 1C). This fold orientation and the associated axial plane foliation requires a N- to NE-directed compression. Similarly, strain analyses from reduction spots in the Proterozoic Kona Formation within the Marquette syncline (Westjohn, 1978) show no evidence of NW-directed compression. These data yield an E-W striking XY principle plane of finite strain (Figure 2B) indicative of N- to NE-directed shortening. Although Klasner (1978) reports sparse late-stage kink bands in the Proterozoic Michigamme Formation with near vertical kink planes striking N. 20° E. and N. 50° W., he attributes these to late-stage block uplift of the Archean basement.

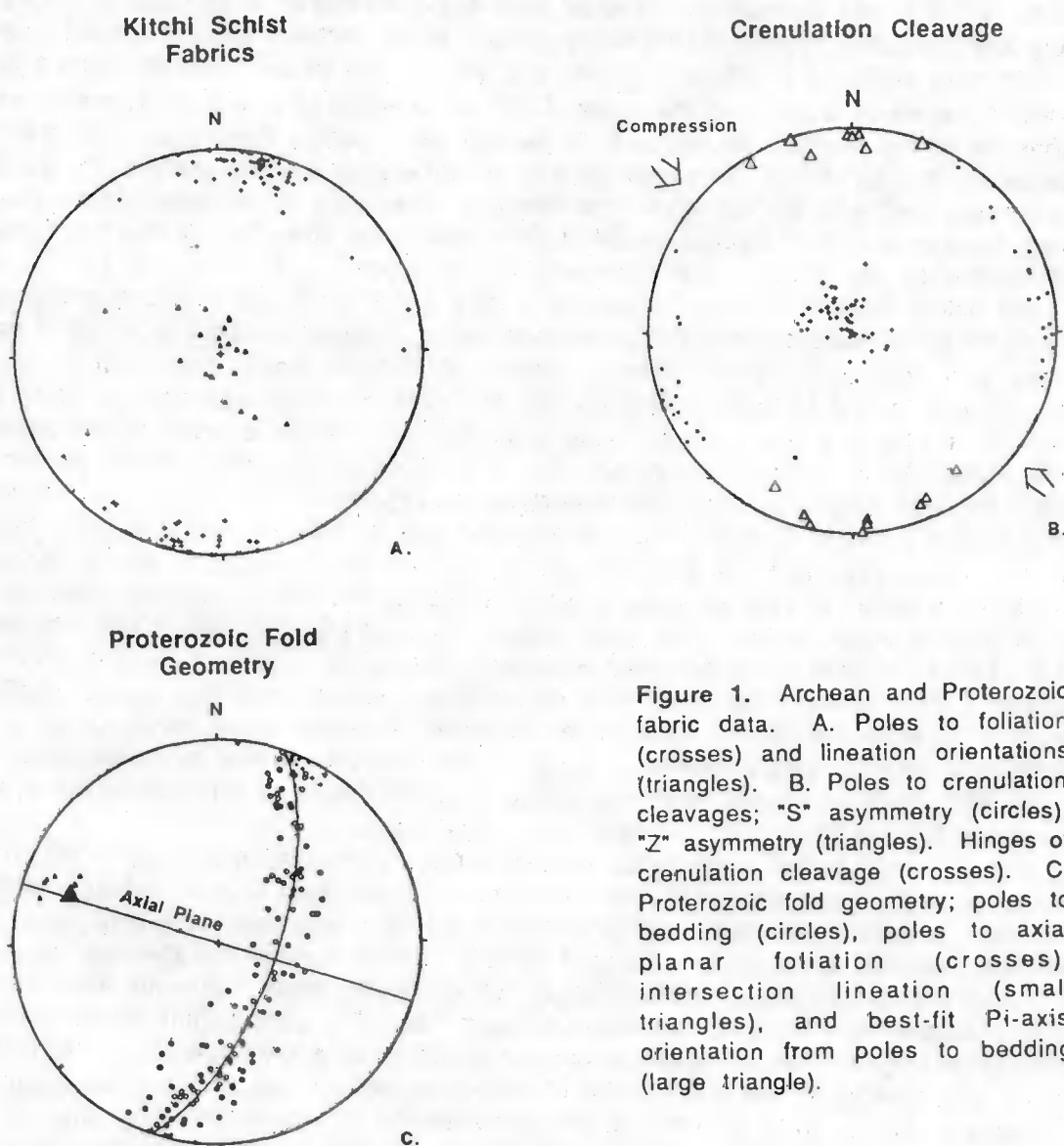


**Figure 1.** Archean and Proterozoic fabric data. A. Poles to foliation (crosses) and lineation orientations (triangles). B. Poles to crenulation cleavages; "S" asymmetry (circles), "Z" asymmetry (triangles). Hinges of crenulation cleavage (crosses). C. Proterozoic fold geometry; poles to bedding (circles), poles to axial planar foliation (crosses), intersection lineation (small triangles), and best-fit Pi-axis orientation from poles to bedding (large triangle).

In summary, although the regional trend of the dominant Archean and Proterozoic foliations is subparallel, the orientation of second deformation conjugate crenulation cleavages in the Archean rocks is incompatible with the deformation features recognized in the adjacent Proterozoic rocks. These data therefore suggest that the first and second deformation features we observe in the Archean rocks of this area were not imposed by Proterozoic deformation.

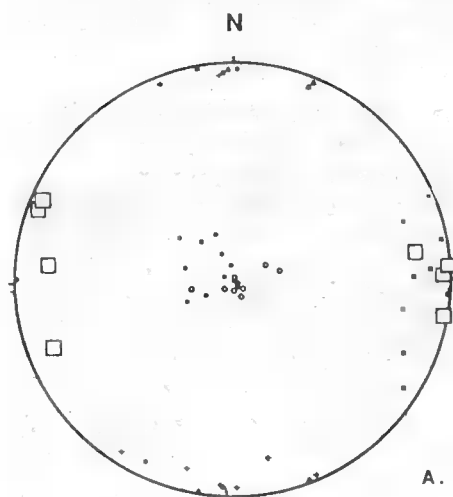
Carter, P.J. Jr., 1989, Finite strain estimates for Archean Mona Schist pillows and Enchantment Lake Formation metawackes in the eastern upper peninsula of Michigan: Unpublished M.S. Thesis, Michigan State University, East Lansing MI., 97 p.

Cosgrove, J. W., 1976, The formation of crenulation cleavage: Jour. Geol. Soc. Lond., vol. 132, p. 155-178.

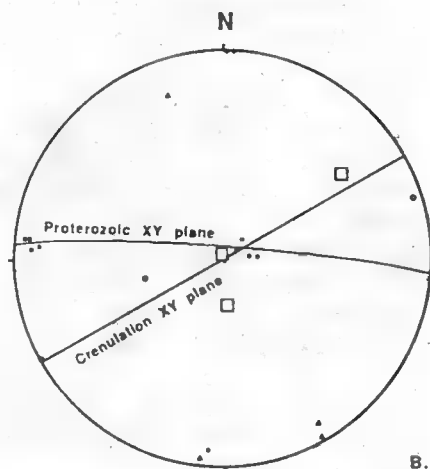
Klasner, 1978, Penokean deformation and associated metamorphism in the western Marquette Range, northern Michigan: Geol. Soc. Amer. Bull., vol. 89, p. 711-722.

Westjohn, D.B., 1978, Finite strain in the Precambrian Kona Formation, Marquette County, Michigan: Unpublished M.S. thesis, Michigan State Univ., East Lansing MI., 72 p.

#### Principle Axes of Finite Strain, Kitchi and Mona Schist



#### Principle Axes of Finite Strain, Archean (Crenulated) and Proterozoic Rocks



#### Log Flinn plot of Finite Strains

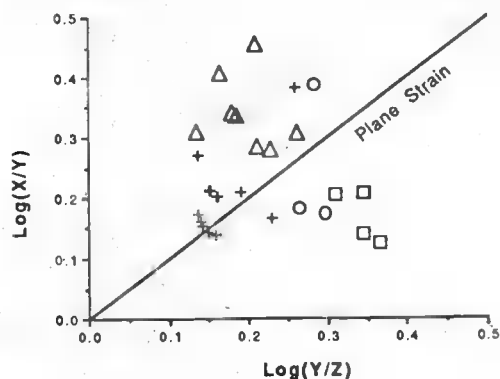


**Figure 2** (above). Principle axes of finite strain, Archean and Proterozoic rocks. **A.** X, Y, and Z axes from the Kitchi Schist are open circles, open squares, and triangles (this study). X, Y, and Z axes from the Mona Schist are shaded circles, shaded squares, and crosses (Carter, 1989). **B.** X, Y, and Z axes from the crenulated Archean Mona Schist (srt member) are open circles, open squares, and triangles (this study). X, Y, and Z axes from the Proterozoic Kona Formation are shaded circles, shaded squares, and crosses (Westjohn, 1978). **Figure 3** (left). Log Flinn plot of finite strains from the Kitchi Schist (triangles) (this study), Mona Schist (crosses) (Carter, 1989), srt member of Mona Schist (circles) (this study), and the Proterozoic Kona Formation (squares) (Westjohn, 1978).

## EXPLORATION AND MINING ACTIVITY IN NORTHWESTERN ONTARIO

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The mineral sector in Ontario provided 25,962 direct jobs and produced materials with a total Canadian dollar value of \$6,853,756,000 in 1988.

This poster displays the producing mines and advanced mineral exploration projects in the Northwestern Region of the Province of Ontario. Currently there are 8 producing gold mines, 4 base metal mines, 6 stone quarries, and 5 seasonal amethyst mines in the region employing 2152, 1133, 26 and 36 people respectively. There are also 22 projects in advanced exploration. In 1989, the region produced approximately: 50,843 kg (kilograms) of gold; 125,310 kg of silver; 30,514,973 kg of copper; 6,667,808 kg of nickel; 3,794,754 kg of lead; and 112,799,350 kg of zinc - for a total Canadian dollar value of \$1,225,284,402. Representative ore samples of Northwestern Ontario are also on display.

A statistical summary booklet that tabulates regional data such as reserves, grades, location, ownership and development is available free of charge in both English and French.

## LOWER PROTEROZOIC GLACIOGENIC DEPOSITS: A NORTH AMERICA - BALTIC CONNECTION?

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### ABSTRACT

Lower Proterozoic glaciogenic deposits of approximately the same age(?) occur at several localities in North America and on the Baltic (Fennoscandian) Shield in Finland and in the USSR just east of Finland. The main evidence for a glacial history is the association of fine-grained laminated units containing oversized limestones (some clearly "dropstones"), with diamictite (matrix-supported conglomerate).

This "diamictite-dropstone laminite" association has long been known in the Huronian Supergroup of Ontario, especially in the Gowganda Formation (e.g., Young, 1981), but also in the slightly older Ramsey Lake and Bruce Formations. In the Upper Peninsula of Michigan, the diamictite-dropstone laminite association is present in three units - the Reany Creek (Puffett, 1969) and Enchantment lake (Gair, 1981) Formations of the Marquette Range area and in the Fern Creek Formation (Pettijohn, 1943) of southern Dickinson County, 80 km to the south (Ojakangas, 1984). All three Michigan occurrences are the basal units of the Lower Proterozoic rock column at those localities. Similar deposits are known in southern Wyoming, west of Hudson Bay, and in central Quebec, and an Early Proterozoic glaciation covering about 5 million km<sup>2</sup> was suggested by Young (1970).

Such deposits were recently discovered in eastern Finland in the Sariolian Group of the Karelian Supergroup (Marmo and Ojakangas, 1984). The Urkkavaara Formation, which we have interpreted as glaciomarine, is subdivided into four informal members as follows: a lower argillite member, a graded sandstone member, an upper siltstone-argillite member, and a diamictite member. The lower three members contain dropstones, and the upper siltstone-argillite grades upward into the diamictite facies. Subsequently, Marmo (1986) described three additional members that overlie the initial sequence as follows: an upper graded sandstone member, a parallel-bedded conglomerate member and a massive conglomerate member. He interpreted these three members to be comprised of glaciofluvial sediments. The Urkavaara Formation, about 300 m thick, is capped by a 100 m thick meta-regolith that appears to have been largely conglomeratic rock prior to intensive Early Proterozoic weathering. Close inspection of the same stratigraphic horizon in the Sariolian Group has resulted in the recognition of glaciogenic characteristics in five other areas in eastern and central Finland; some of these localities are separated by 350 km.

Negrutsa and Negrutsa (1981a,b) described 15 diamictite localities in the Sariolian Group and its equivalents, many with associated limestones, in Karelia, USSR; they proposed sedimentary-tectonic and volcanotectonic origins. We visited seven localities in 1988, and diamictite and limestone units are associated in the rock column at each. At one locality, a thick sequence of diamictite is overlain by thinly laminated metasiltstone with dropstones that clearly penetrate and deform the laminae (Ojakangas et al, 1989).

The presence of glaciogenic lithologies in widely spaced areas of sedimentary rocks on the Baltic Shield allows for correlation, as a glaciation is an uncommon "mega-event" related to climatic change (Ojakangas, 1988). If all of these deposits are indeed of the same age, the area on the Baltic Shield that was affected by this Early Proterozoic glaciation had a minimum size of about 500 km by 250 km. If the other diamictite (tilloid) occurrences described by Negrutsa and Negrutsa on the Kola Peninsula in northwesternmost USSR are included, although we have been unable to study those localities to attempt to verify glacial characteristics, the area directly affected by the Early Proterozoic glaciation may be on the order of 200,000 km<sup>2</sup>, suggestive of a continental-scale glaciation.

The rock units in which these glaciogenic rocks occur in Finland and East Karelia are underlain by lava flows dated at about 2450 m.y. and are intruded by dikes and sills dated at about 2180 to 2160 m.y. The Huronian Supergroup has 2450 m.y. lavas at its base and is intruded by Nipissing dikes and sills dated at about 2180 to 2150 m.y.

A contemporaneous or penecontemporaneous glaciation seems likely, and it is possible that the North American and Baltic Shields were in close proximity approximately 2300-2200 m.y. ago (Ojakangas, 1988).

## References Cited

- Marmo, J.S., 1986, Sarioian stratigraphy in the Koli-Kaltimo area, North Karelia, Eastern Finland, in V.A. Sokolov and K.I. Heiskanen, eds., Early Proterozoic of the Baltic Shield: Proceedings of the Finnish-Soviet Symposium held in Petrozavodsk 19-27 August 1985, p. 149-190.
- Marmo, J.S., and Ojakangas, R.W., 1984, Lower Proterozoic glaciogenic deposits, eastern Finland: *Geol. Soc. America Bull.*, v. 95, p. 1055-1062.
- Negrutsa, T.F., and Negrutsa, V.Z. 1981a, Early Proterozoic Lammos tilloids of the Kola Peninsula, U.S.S.R., in Hambrey, M.J. and Harland, W.B.eds., *Earth's Pre-Pleistocene glacial record*: Cambridge Univ. Press, p. 678-680.
- \_\_\_\_\_, \_\_\_\_\_, 1981b, Early Proterozoic Sarioli tilloids in the eastern part of the Baltic Shield, U.S.S.R., in Hambrey M.J., and Harland, W.B., eds., *Earth's Pre-Pleistocene glacial record*, p. 683-686.
- Ojakangas, R.W., 1984, Basal Lower Proterozoic glaciogenic formations, Marquette Range Supergroup, Upper Peninsula, Michigan (Abs.): 30th Institute on Lake Superior Geology Proceedings, Wausau, WI., p. 43.
- \_\_\_\_\_, 1988, Glaciation: an uncommon "mega-event" as a key to intracontinental and intercontinental correlation of early Proterozoic basin fill, North American and Baltic cratons, in K.L. Kleinspehn and C. Paola, eds., *New Perspectives in Basin Analysis*: Springer-Verlag, p. 431-444.
- \_\_\_\_\_, Marmo, J.S. and Heiskanen, K.I., 1989, Lower Proterozoic glaciogenic deposits: Finland and U.S.S.R., Baltic Craton (Abs.): 28th International Geologic Congress Abstracts, Washington, D.C., p. 2-542.
- Pettijohn, F.J., 1943, Basal Huronian Conglomerates of Menominee and Calumet districts, Michigan: *Jour. Geology*, v. 51, p. 387-397.
- Puffett, W.P., 1969, The Reany Creek Formation, Marquette County, Michigan: *Bull U.S. Geol. Surv.* 1274-F, p. F1-F25.
- Young, G.M., 1970, An extensive early Proterozoic glaciation in North America? *Palaeogeogr., Palaeoclimat., Palaeoecol.*, v. 7, p. 85-101.
- \_\_\_\_\_, 1981, The early Proterozoic Gowganda Formation, Ontario, Canada: in Hambray, M.J. and Harland, W.B. (eds.), *Earth's Pre-Pleistocene Glacial Record*. Cambridge Univ. Press, p. 807-812.

# Petrography, Mineral Chemistry, and Geothermobarometry of Mafic Granulite and Eclogite Nodules from Upper Michigan Kimberlites.

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Accidental xenoliths and xenocrysts contained within diatremes from the Michigan Kimberlite Province (Cannon and Mudry, 1981; Jarvis and Kalliokoski, 1988) represent one of the few means of sampling the deep Phanerozoic crust and upper mantle beneath the southern Superior Province. These materials are vital both for investigating the composition and chemical history of the deep lithosphere, and for testing lithospheric structural models derived from geophysical data (i.e., GLIMPSE studies). Diatremes were emplaced during the Jurassic (Jarvis and Kalliokoski, 1988) into a geologically complex region along the southern boundary of the Superior Province in Upper Michigan (Fig. 1). Although the lithosphere in this area formed and/or stabilized during the late Archean, it was likely modified during subsequent tectono-magmatic processes associated with Lower Proterozoic Penokean orogenesis and Middle Proterozoic Midcontinent Rifting. This paper presents initial results of a nodule study whose long range goal is to better understand the petrological and geochemical structure of the continental lithosphere and its modification through time.

Data reported here were obtained from discrete

granulite and eclogite nodules collected by William Jarvis of Jack Murphy, Trustee, from trenches excavated in the Lake Ellen and Site 69 pipes (Fig. 1). Nodules range in size from 2 to 8 cm in diameter and weigh between 20 and 400 g. Paleozoic carbonate and low-grade metamorphic clasts were largely excluded. Although the present nodule suite is limited (~50 nodules) and does not represent an unbiased sampling of the lithospheric column, lithologies described here form a substantial proportion of the "deep" xenolith population. The Site 69 pipe contains a variety of mafic amphibolites and granulites, but no discrete upper mantle and/or ultramafic nodules. In contrast, the Lake Ellen pipe includes a variety of eclogites, pyroxenites, garnet peridotites, spinel peridotites, and mantle xenocrysts (McGee and Hearn, 1983) in addition to less abundant mafic granulites. Attempts to better quantify xenolith populations are under investigation. The current results focus on lower crustal granulite and eclogite nodules from the two pipes.

**GRANULITES:** Granulites from both pipes nearly all have mafic compositions containing plagioclase (18-37 vol.%) and clinopyroxene (19-40%) along with garnet (16-42%)  $\pm$  amphibole (0-11% in gt-bearing rocks, up to 37% in gt-free rocks). Minor (1-2%) ilmenite (occasionally rutile) is ubiquitous, while quartz and orthopyroxene may be present, but only in minor amounts. A single nodule of plg+gt+qtz with minor rut+cpx represents the most-"felsic" granulite observed. Granulites exhibit nonfoliated, equigranular (0.5-1.5 mm diam.), granoblastic textures. Although no obvious fabrics are observed in individual nodules, some thin sections show non-homogeneous distributions of phases. Mineral compositions within single nodules vary only within small limits suggesting that local equilibrium was achieved. Plagioclase is most sodic (An<sub>25-40</sub>) in gt-bearing assemblages and most calcic (An<sub>50-55</sub>) in gt-free assemblages (Fig. 2). Clinopyroxenes contain low Cr<sub>2</sub>O<sub>3</sub> (<0.04 wt.%), substantial Al<sub>2</sub>O<sub>3</sub> and Na<sub>2</sub>O (3-5 wt.%, and 1-2 wt.%, resp.) and Mg#s (Mg/(Mg+Fe<sup>2+</sup>)) of 0.71-0.80. Ilmenite contains 1-2 wt.% MgO in gt-bearing rocks and 0.2-0.7 wt.% in

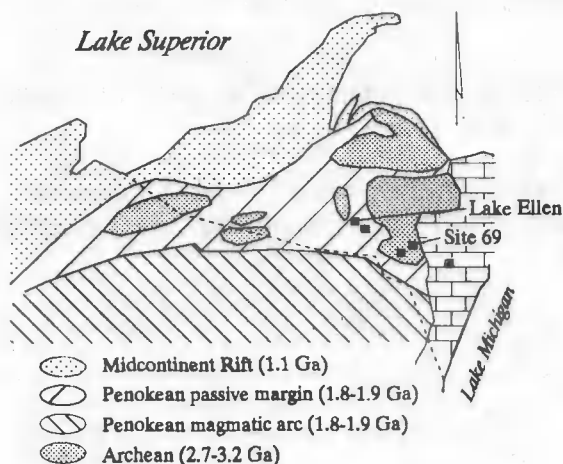


Fig. 1: General Geological Map.

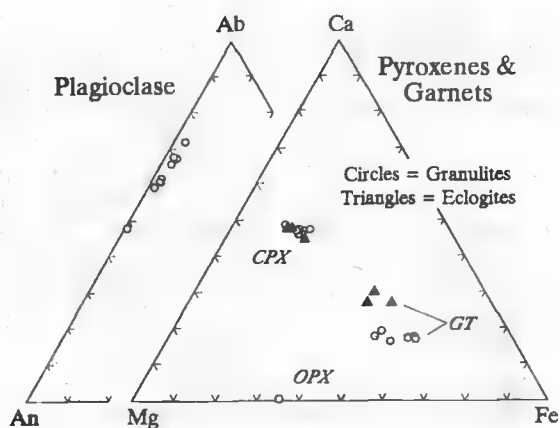


Fig. 2: Plagioclase, Pyroxene and Garnet Chemistry.

gt-free rocks. Orange, almandine-rich garnet contains 23-27 wt.%  $\text{FeO}_t$ , 6-9 wt.%  $\text{MgO}$ , and 6-7 wt.%  $\text{CaO}$  (Fig. 2). Garnets in some nodules are graphically intergrown with both cpx and qtz. Varying degrees of retrograde alteration affect garnets beginning with fibrous, green-black rims progressing to a distinct pseudomorphic replacement by fine, plg-sp-chl aggregates. Amphiboles in gt-bearing granulites exhibit a similar mottling of fine-grained opaques, and may represent recrystallization of kelyphytic aggregates. Many granulites also show a network of serpentine/chlorite alteration along grain boundaries adjacent to fresh cpx and plg. This network may extend into grains along cracks where it sometimes terminates in patchy brown, mesostasis-like material. These features are interpreted as devitrified and altered decompression melts formed during nodule transport and emplacement.

**ECLOGITES:** Eclogites constitute the largest percentage (85%) of upper mantle xenoliths previously reported from the Lake Ellen kimberlite (McGee and Hearn, 1983). The three sanidine eclogites included in the present suite are texturally and compositionally similar to those described earlier. Mineral assemblages consists of omphacitic clinopyroxene (49-58%) + garnet (26-38%) + K-

feldspar (1-10%) + rutile (1-2%) with accessory Cl-apatite, silica, and Fe sulfide. Hearn and McGee (1983) also report kyanite- and corundum-bearing eclogites with similar major-phase compositions. Eclogites exhibit granoblastic-polygonal textures (0.5-3 mm diam.) with no obvious fabrics on a thin section scale. Only minor intragranular compositional variations are present. Omphacitic clinopyroxenes (Fig. 2) have high  $\text{Al}_2\text{O}_3$  (14.8 wt.%) and  $\text{Na}_2\text{O}$  (7.7 wt.%), low  $\text{Cr}_2\text{O}_3$  (<0.07 wt.%), and Mg#s between 0.72-0.74. Orange garnets (Fig. 2) are high in iron ( $\text{FeO}_t = 20.5$  wt.%, Mg# = 0.39-0.42) and, like pyroxene, low in  $\text{Cr}_2\text{O}_3$  (<0.05 wt.%). K-feldspar is unequally distributed within single thin sections and contains high  $\text{K}_2\text{O}$  (~16.3 wt.%), low  $\text{Na}_2\text{O}$  (<0.5 wt.%), and appreciable  $\text{BaO}$  (0.3-1.1 wt.%). The presence of small, rounded inclusions of K-feldspar in pyroxene and garnet with similar compositions indicates that K-feldspar is a primary phase. Reddish-brown rutile is relatively pure with only small amounts of  $\text{FeO}$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{ZrO}_2$  (<1.5, 0.5, and 0.4 wt.%, resp.). Degree of alteration in eclogites varies widely. Clinopyroxene reacts most readily; first around grain boundaries and then along internal fractures producing a net-like fabric. Omphacitic pyroxenes in highly altered nodules are completely replaced by milky, augite-rich aggregates. Large books of biotite may also be developed.

**WHOLE ROCK COMPOSITIONS:** Granulite whole rock compositions reconstructed from mineral chemistry and modal proportions yield close approximations to moderately-evolved, high- $\text{Al}_2\text{O}_3$  basaltic liquids (Table 1). Typical normative mineralogy includes 50-60% Pl ( $\text{An}_{50-70}$ ), 5-15% Ol, 20-35% Di+Hy. The single "felsic" nodule yields an andesitic composition and contains 13% normative Qz and 3% normative corundum. Eclogites yield high-Al, basaltic, whole rock compositions similar to the mafic granulites with the exception of higher alkalis, and  $\text{TiO}_2$ . As a result, the two analyzed eclogites are Ne normative (6-8% Ne) with otherwise comparable normative Pl, Ol and Di.

TABLE 1: Average Reconstructed Whole Rock Compositions for Granulites and Eclogites

|                  | N | $\text{SiO}_2$ | $\text{TiO}_2$ | $\text{Al}_2\text{O}_3$ | $\text{FeO}$ | $\text{MnO}$ | $\text{MgO}$ | $\text{CaO}$ | $\text{Na}_2\text{O}$ | $\text{K}_2\text{O}$ | $\text{Cr}_2\text{O}_3$ | Total |
|------------------|---|----------------|----------------|-------------------------|--------------|--------------|--------------|--------------|-----------------------|----------------------|-------------------------|-------|
| Mafic Granulites | 6 | 49.18          | 1.16           | 16.01                   | 12.26        | 0.25         | 6.45         | 10.70        | 3.12                  | 0.24                 | 0.02                    | 99.39 |
| Intermed. Gran.  | 1 | 55.98          | 0.88           | 18.74                   | 11.09        | 0.24         | 3.93         | 6.00         | 2.86                  | 0.20                 | 0.01                    | 99.93 |
| Eclogite         | 2 | 49.49          | 1.74           | 17.28                   | 9.48         | 0.15         | 6.20         | 9.86         | 4.43                  | 1.00                 | 0.04                    | 99.64 |

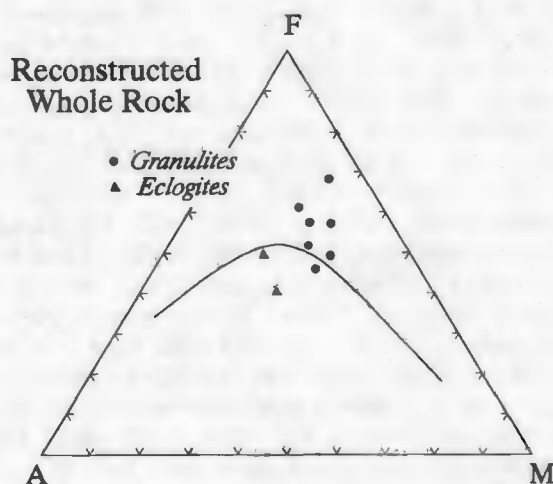


Fig. 3: AFM Diagram For Reconstructed Whole Rocks.

**GEO-THERMOBAROMETRY:** Preliminary P-T estimates from unzoned Gt-Cpx-Plg±Qtz±Opx assemblages in granulites yield temperature ranging from 712-760°C and pressures from 9-12 kb. Results obtained using several different thermobarometers show reasonable agreement ( $\pm 10^\circ\text{C}$  and  $\pm 1.5$  kb). These results are comparable to P-T conditions observed in regional granulite terrains (Bohlen, 1987) although pressures for nodules are higher than most uplifted granulite terrains at similar temperatures. Estimated pressures correspond to depths of 30-42 km. Depths to seismic-Moho reflectors in this area have been measured at 36-42 km (Behrendt, in press). Establishing P-T conditions for eclogites is more difficult due the lack of a reliable geobarometer for gt-cpx assemblages. Eclogite gt-cpx temperatures range between 980-1070°C for pressures of 15-40 kb. The presence of kyanite-eclogites in this temperature range requires a minimum of 14 kb (McGee and Hearn, 1983). Cpx-opx composite xenocrysts (McGee and Hearn, 1983) yield P-T estimates of 840-920°C and 12-17 kb. Although the opx pressures are questionable for these xenocrysts, the combined data preserve a consistent geotherm (Fig. 4) intermediate between hot, rift conditions (Berg et al., 1989) and cold, shield conditions (Pollack and Chapman, 1977).

**CONCLUSIONS:** Initial results indicate that granulites were derived from mafic igneous protoliths which equilibrated within the lower crust at depths as great as the seismic-Moho. No granulites with metasedimentary affinities have yet been recognized. These data are consistent with models of a mafic lower crust derived through

underplating and injection of basaltic magmas (Bohlen, 1987; Griffin and O'Reilly, 1987). Eclogites with similar compositions may represent basaltic magmas emplaced below the seismic-Moho. At least three major tectono-magmatic episodes at  $\sim 2.7$ ,  $\sim 1.85$  and  $\sim 1.10$  Ga could be responsible for emplacement of nodule protoliths. Seismic reflectors throughout the Lake Superior region are interpreted to have origins associated with Midcontinent Rifting (Behrendt et al., in press). However, nearby tholeiitic volcanics associated with Penokean passive margin assemblages, as well as Archean metavolcanics, indicate older potential magmatic sources. Further geochemical, geochronological, and isotopic studies which may help constrain protolith petrogenesis are currently in progress.

**References:** Behrendt et al., (1990) *Tectonophysics* 172, (in press); Berg et al. (1989) *EPSL* 93, 98-108; Bohlen (1987) *J Geol.* 95, 617-632; Cannon & Mudry (1980) *USGS Circ* 842; Griffin & O'Reilly (1987) in, P.H. Nixon, ed, *Mantle Xenoliths*; J. Willey & Sons, 413-430; Jarvis & Kalliokoski (1988) *Inst L. Super Geol* 34, 46-48; McGee & Hearn (1983) *USGS Open-file Rep* 83-156, 22p; MacGregor (1974) *Am Mineral* 59, 110-119; Pollack & Chapman (1977) *Tectonophysics* 38, 279-296

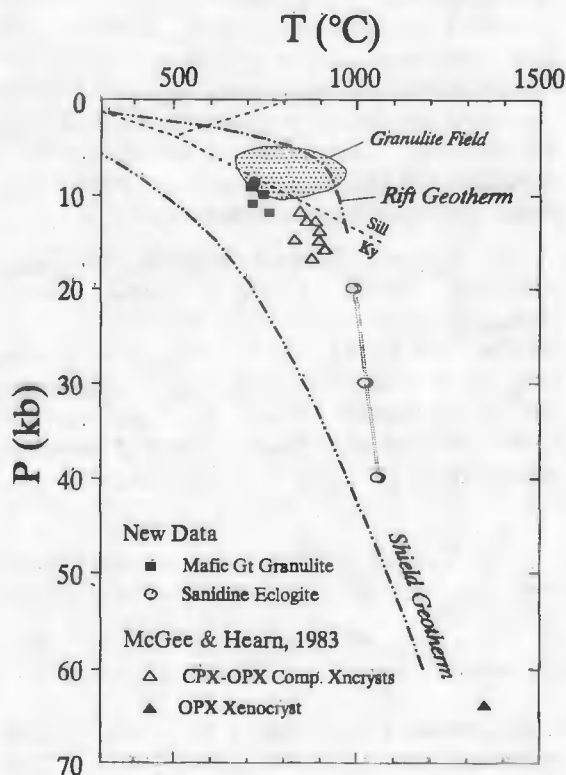


Fig. 4: Calculated P-T conditions for Michigan nodules.

## ARCHEAN AND PENOKEAN STRAINS IN THE NORTHERN COMPLEX, MARQUETTE MINERAL DISTRICT, MICHIGAN

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The complexity of dynamothermal metamorphism of Archean rocks in the Marquette District, Michigan was recognized by the earliest workers (Williams, 1891; Van Hise and Leith, 1911). Two Archean metamorphic events were documented by Gair and Thaden (1968) but the problems associated with sorting out these Archean events from the Penokean overprint remain with us. Modern techniques of quantitative strain analysis give promise of solving some of these problems. Recent work showing the close similarity of strain ellipsoid axes orientations, and magnitudes in the Archean rocks to those of rocks in the Marquette Supergroup (Carter, 1989, p. 69) suggested that either the Archean rocks were undeformed prior to the Penokean, and thus record only Penokean strain, or that the measured strains in the Archean rocks are indeed Archean but the rocks behaved in a brittle fashion during the Penokean deformation. In this paper I argue for a third interpretation, namely that the Archean rock fabrics record both Archean and Penokean strains, in a complex sequence of events.

Strain measurements in variolitic pillow lavas of the Mona Schist between Marquette and Negaunee indicate north-south horizontal shortening of 27-36% and vertical extension of 40-60%, and near plane strain (Carter, 1989). These data are consistent with those documented for slates of the Kona Formation and quartzites of the Mesnard and Ajibik Formations of the Marquette Supergroup (Westjohn, 1978; 1986; 1987). New strain measurements of pressure fringes in a chlorite schist from the lower member of the Mona Schist show a minimum vertical extension of 100%. The pressure fringes are quartz-chlorite fibers grown on the ends of rigid hematite porphyroblasts. These data suggest the interpretation that Archean rocks of varying strengths have responded differently, and thus yield heterogeneous strain indicators. The variolitic pillow lavas record primarily Archean strains whereas the pressure fringes, developed in more ductile rocks, record larger amounts of Archean strain as well as an additional increment of Penokean strain. Penokean deformation in the Archean basement is concentrated in high strain shear zones and within the more ductile lithologies.

The division of the Mona Schist into an upper (Lighthouse Point) and lower member by Gair and Thaden, 1968) was based, in part, on the division between the banded greenstones of the upper part and the massive greenstones of the lower part. They recognized, however, the higher metamorphic grade of the layered amphibolitic schist characteristic of the Lighthouse Point member. I suggest that the boundary separating the members of the Mona Schist is tectonic rather than stratigraphic. In addition to the abrupt change in metamorphic grade, the strain fabrics are different across the boundary. Mylonitic fabrics in the meta-rhyodacites interlayered with the Lighthouse Point Member suggest Archean strains whereas S-C structures in associated laminated flinty quartz sericite rock indicate up-to-the-north movement consistent in sense and position with a Penokean zone of displacement to account for the higher metamorphic grade in the Lighthouse Point member (upthrown) and lower grade in the Lower (downthrown) member. These same rocks also show asymmetrically developed kink bands which are interpreted as the Archean basement manifestation of the axial shortening and cross-folding developed in the Animikie rocks of the Marquette synclinorium.

The Archean rocks north of the Marquette synclinorium, the "northern complex" appear to show three strain regimes. To the north, in the Compeau Creek gneiss, ductile shear zones provide evidence of Archean reactivation of diabase dikes. A dextral transpression regime seems well-developed in this zone. The central sector, mainly the Lighthouse Point Member, has a complex strain pattern with mylonitic fabric locally in its felsic layers and vertically stretched boudins in the amphibolitic schist. Some geologists have speculated that the lenticular layers in this unit are actually extremely flattened pillows. If that is correct, the Lighthouse Point member is much more flattened as well as of higher metamorphic grade than the lower member. The strain fabric of the lower member is dominated by vertical extension ranging from essentially undeformed to 60% in variolitic pillow lavas to a minimum of 100% in chlorite schists and slaty units. Future work will be directed at further documenting the strain partitioning within the northern complex and attempting to establish the relationships between the Archean and Penokean deformations.

#### REFERENCES CITED

- Carter, P. J., Jr., 1989, Finite strain estimations for Archean Mona Schist pillows and early Proterozoic Enchantment Lake Formation. Metawackes in the eastern upper peninsula of Michigan: Michigan State Univ. unpub. M. S. thesis, 97 p.

Gair, J. E. and Thaden, R. E., 1968, The Geology of the Marquette and Sands  
Quadrangles, Marquette County, Michigan: U.S. Geol. Survey Prof.  
Paper 397, 77 p.

Van Hise C. R. and Leith, C. K., 1911, The Geology of the Lake Superior  
Region: U.S. Geol. Survey Mon. 52, 641 p.

Williams, G. H., 1891, The greenstone schist areas of the Menominee and  
Marquette regions of Michigan: U.S. Geol. Survey Bull. 62, 238 p.

## **FINNISH PROTEROZOIC GOLD OCCURRENCES AND IMPLICATIONS FOR THE LAKE SUPERIOR REGION**

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The Proterozoic geology of Finland is similar to that of the Lake Superior region and is consistent with Proterozoic plate reconstructions which suggest that Finland and Greenland were connected with North America. Thus, it is appropriate to use the geologic setting of Proterozoic gold occurrences in Finland as analogs for the Lake Superior region. In the Proterozoic of Finland there are a significant number (34) of gold occurrences of economic interest, in the Lapland greenstone belt and in the Lapland granulite terrane of north Finland, and in the Svecokarelian complex of south Finland. These three areas have been interpreted as subparallel rift zones. The Lapland greenstone belt was intracontinental whereas the other two developed oceanic crust.

The Lapland granulite terrane is composed of graywackes which underwent granulitization around 2.1 to 2.0 Ga. This terrane was overthrust to the southwest onto Archean basement and the Lapland greenstone belt. Placer gold has been recovered in small amounts from this terrane since the late 1800's. This gold was derived from retrogressive shear zones.

The Lapland greenstone belt of early Proterozoic age (2.5 to 2.0 Ga) consists of bimodal volcanics overlain by quartz-rich sediments in the lower part and of komatiitic to tholeiitic volcanics with related volcanoclastics in the upper part. Mafic intrusions are common at 2.4 and 2.2 Ga. These rocks were deformed at about 1.9 Ga in a style that resembled foreland fold thrust belts. Synorogenic granitoids, clastic sediments, and felsic volcanics were followed by postorogenic granites. Gold mineralization occurs in quartz-carbonate veins hosted by altered ultramafic and mafic rocks, in quartz-carbonate veins associated with felsic dikes and related granitoids, and in disseminated sulfides or breccia pipes hosted by albitized quartzites. Faults, shear zones, or folds play a role in localization of all occurrences. Gold is epigenetic and emplaced after the peak of regional greenschist facies metamorphism and deformation.

The Svecokarelian complex ranges in age from about 2.2 to 1.75 Ga. It consists of a thick succession of metamorphosed platform to deep-water turbidites. Mafic igneous rocks are a small component of the complex. These rocks were deformed between about 2.0 to 1.75 Ga during the Svecokarelian orogeny.

About three quarters of the complex consists of syntectonic tonalite to granodiorite and associated intermediate to felsic volcanics. A major portion of the complex represents juvenile crust. Gold is hosted by tonalite to quartz diorite stocks and intermediate volcanics/intrusives. A few occurrences are in supracrustal rocks. Metamorphic grade of the host rocks is amphibolite facies. Gold tends to be associated with either lithological contacts or shear zones. Alteration is characterized by quartz-sericite-biotite and K-feldspar and lacks carbonates. Gold was likely emplaced during the late stages of the orogeny and may be linked with magmatic processes.

Geologic environments exist in the Lake Superior region that are very similar to gold bearing ones in Finland. Thus, it is reasonable to suspect that numerous significant gold occurrences exist in early Proterozoic rocks of the Lake Superior region.

# NEW EVIDENCE THAT LIMESTONE MT., MICHIGAN, IS PART OF A LARGE IMPACT STRUCTURE

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Rising abruptly to a height of about 100 m above the low ground which immediately surrounds it, Limestone Mt. is, topographically, a rather impressive feature. When it was discovered that the "mountain" consists mainly of limestone (or dolostone), whereas all but one of the other high hills in the area are sandstone, quarrymen and geologists were immediately attracted to it. The other projecting mass of limestone in the area is Sherman Hill (see Fig. 1), much smaller and lower than "the mountain."

Geologists soon found out that the (unmetamorphosed) limestone is full of fossils, and, from these, that the age of the rock is Ordovician. In the "mountain," the layers are not horizontal but warped down in a pronounced syncline and displaced by numerous small faults. The same is true to a lesser degree of Sherman Hill. This led to considerable speculation regarding the cause of the deformation, which involves, not only the two hills, but also a good deal of the neighboring sandstone (Jacobsville) where this is visible. Fig. 1 shows most of the known exposures of Jacobsville which are relevant to this paper. These exposures are low and inconspicuous. Obviously, the limestone is much more resistant to erosion.

Most structural studies have been aimed primarily at "the mountain." In relatively recent years, geophysics has played a part in these studies and some geophysicists have covered a good deal of territory beyond Limestone Mt. and its immediate vicinity. For example, Campbell, in preparing a 1952 M.S. thesis on the "Silver Mountain area" (1) did a good deal of ground magnetic and gravity work as far north as Limestone Mt. (Silver Mt. is a projecting knob of basalt tens of miles to the southwest.) The U.S. Geological Survey published in 1965 a set of (quadrangle by quadrangle) aeromagnetic maps covering the area around Limestone Mt. The magnetic contours shown in Fig. 1 were traced from these maps.

Hoehl's massive M.S. thesis (2) provides a virtually complete bibliography of the relevant literature up to 1981. The only contribution which he missed, an important one from my point of view, is the first large tectonic map of the U.S., published in 1944 by the National Research Council. Walter Bucher, who regarded many local disturbances in otherwise flat-lying sedimentary rock as evidence of "cryptovolcanic" activity, was on the committee that put this map together, and presumably responsible for getting Limestone Mt. on it as an example of this kind of activity. A goodly number of geologists have subsequently reinterpreted these structures as due to the sudden collision of a flying oversize meteorite, planetesimal, or comet with the earth's surface. Any such collision is bound to result in an awesome explosion which excavates a crater very much larger than the projectile itself and causes deformation well beyond the boundaries of the crater and below its bottom. Some geologists still adhere to the idea that this kind of deformation, of which the downward effects remain long after the crater itself has been eroded away, is due to vulcanism. Others, unwilling to take sides, refer to the structures in question as the result of some unidentified kind of "cryptoexplosion."

Except for the circle, which I have drawn in rather arbitrarily on the assumption that the disturbance recorded by exposures on Limestone Mt., Sherman Hill, and sandstone to the southeast is in fact the result of impact, Fig. 1 is mostly factual. I have been convinced of this for quite some time but heretofore have been uncertain as to where the center of the structure was likely to be and, consequently as to size of the circle.

In a first try at locating the center, I was guided mainly by the M-shaped series of exposures (Fig. 1) between Limestone Mt. and the village of Pelkie. These are the surface expression of a slightly more resistant layer in the Jacobsville which here is folded into a pair of north-plunging anticlines. A number of people who have studied large, well-exposed impact structures have noticed similar anticlines plunging away from what is generally referred to as a "central uplift." Central uplifts are characteristic of impact structures which have a diameter of more than 2-3 km. If the direction of plunge were always directly away from the uplift, then the center of the Limestone Mt. structure should be somewhere on a broad line extending southward in the direction of the axes of these two folds. Result: a somewhat smaller circle than the one I have drawn on Fig. 1, assuming that the distances from Limestone Mt. and Sherman Hill to the center of the structure are, for some reason or other, about the same. Unfortunately, the plunge is now always directly away from a central uplift, as anyone can see who examines Plate 3 of Professional Paper 599-H issued in 1972 by the USGS. This paper describes a "cryptoexplosion" structure in southwest Texas named after the peak which crowns its central uplift: Sierra Madera.

The magnetic high near the center of Fig. 1 now seems to me a much more reliable indicator of the actual location of the (assumed) uplift which lies at the center of the (assumed) impact structure named after Limestone Mt. One thing all the magnetic people agree on is that there is a slightly curving string of magnetic highs beginning several tens of miles to the southwest and petering out rather abruptly a short distance north of Limestone Mt. These highs are generally attributed to a buried ridge of basalt which makes its last surface appearance on the way to Limestone Mt. in the aforementioned Silver Mt. Keweenaw basalt similar to, and presumably an extension of, that which forms the backbone of the Keweenaw Peninsula is thought to underlie most of the area where Jacobsville sandstone is now present directly below whatever unconsolidated material may lie on top of it. As it happens, the strong magnetic high which I have chosen as indicating the location of the (assumed) central uplift in the Limestone Mt. structure is several km southeast of the main string of magnetic highs. Meshref and Hinze (3) have explained this as due to a horizontally-small block, bounded on all sides by faults, having been inexplicably pushed closer to the surface at this particular location.

Many things happen as, and soon after, the initial crater is excavated. They are so numerous, so complex, and so variable--depending on a number of factors--that to describe them all in an abstract or depict their effects accurately in a diagrammatic cross-section (Fig. 2) is impossible. The rise of a central uplift in a crater of the size suggested here is more or less inevitable. Considerable downsiding of large and small slices of the original steep

crater walls is also more or less inevitable. In my cross-section I have shown Limestone Mt. as having dropped down below its original level riding on top of a single huge slide block. Another possibility is that it may have dropped down into a rift ("ring graben") that developed in the rock surrounding the original crater as its walls, momentarily compressed by the force of the explosion, bounced back toward, and even beyond, their original location. This might better explain the fact that, in some places on the east side of "the mountain," rock layers are bent sharply upward as if dragged into that position by downward movement relative to a (hidden) fault a little farther east. In either case the diameter of the proposed disturbed area indicated by the circle on Fig. 1 remains the same. Its outer limits are set by apparently undisturbed exposures of Jacobsville along the west branch of the Otter River to the north and below the dam responsible for Prickett Lake to the south.

So much for theory. Now what about evidence to support it, as promised by the title to this paper? The evidence is divisible into two categories: (1) "in situ," and (2) transported. The "in situ" evidence is derived mainly from the isolated exposure of Jacobsville about 2.5 km due west of the peak of the magnetic high. Examination of a thin section of rock here reveals that most of the original pore space between sand grains has been filled in with small angular fragments in what is now glass, or partly crystallized glass--evidently a fluid mush when squeezed into place. Also the original sand grains, in some cases more or less crushed, have been squashed together, implying a temporary, somewhat plastic condition. These two factors combined are probably responsible for the fact that, among local well drillers, the sandstone near the magnetic high has a reputation for "tightness," meaning that it is reluctant to yield an adequate supply of groundwater. It may be mentioned also that the bedding visible in this small exposure dips about 20° west. This is as observed in small blocks pried out from between intersecting joints. We may be dealing here with cross-bedding, a very common feature in the Jacobsville. If it is "true" (overall?) bedding, the dip is at least consistent with the idea of a central uplift to the east, which must have been accompanied by some outward tilting of adjoining sediments.

The transported evidence is found in thin mud flows apparently derived from retreating glacial ice and intercalated between much thicker layers of outwash sand. These assumed mudflows, heavily laden with slightly rounded pebbles and cobbles, are to be seen in two sandpits a short distance east of the village of Alston, as shown in Fig. 1. Although the direction of the last ice advance was from the northeast, indicated by drumlin-like low hills in this area, suggesting that the cobbles and pebbles in the mudflows should have come from some place well to the north of the area of "tight" sand surrounding the (proposed) central uplift, thin sections of a few of the harder ones composed of sandstone show exactly the same sort of metamorphism exhibited by thin sections cut from the isolated exposure of bedrock close to the (assumed) central uplift.

#### REFERENCES

- (1) Campbell, R. E., 1952, "Geophysical Investigation of the Silver Mountain Area, Houghton County, Michigan," unpublished M.S. thesis, Michigan Technological University.
- (2) Hoehl, E. J., 1981, "Geophysical Investigation of the Limestone Mountain Area of Baraga and Houghton Counties, Michigan," unpublished M.S. thesis, Michigan Technological University.
- (3) Meshref, W. M., and W. J. Hinze, 1970, "Geologic Interpretation of Aeromagnetic Data in Western Upper Peninsula of Michigan," Michigan Geological Survey, Report of Investigation 12.

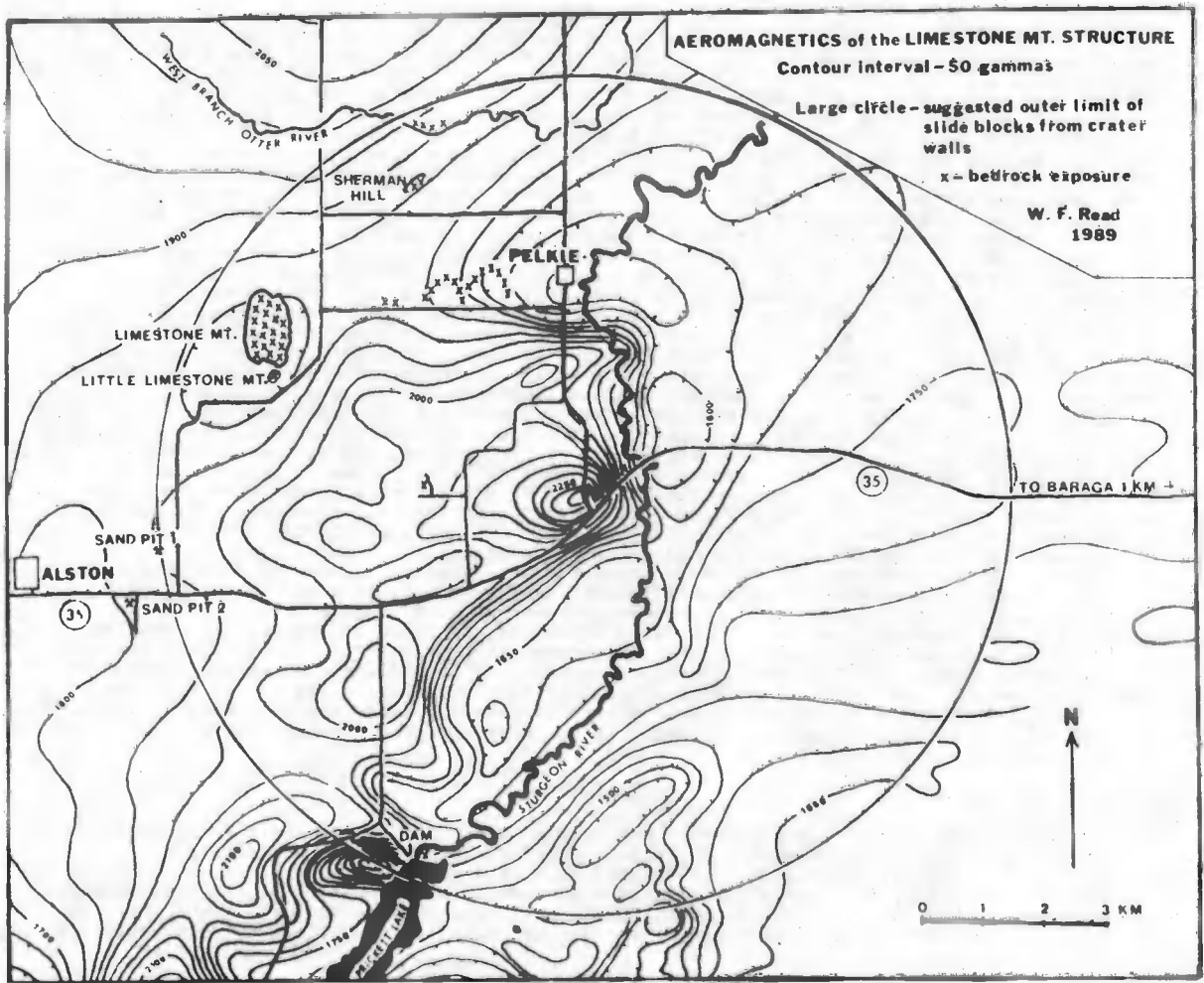


Fig. 1

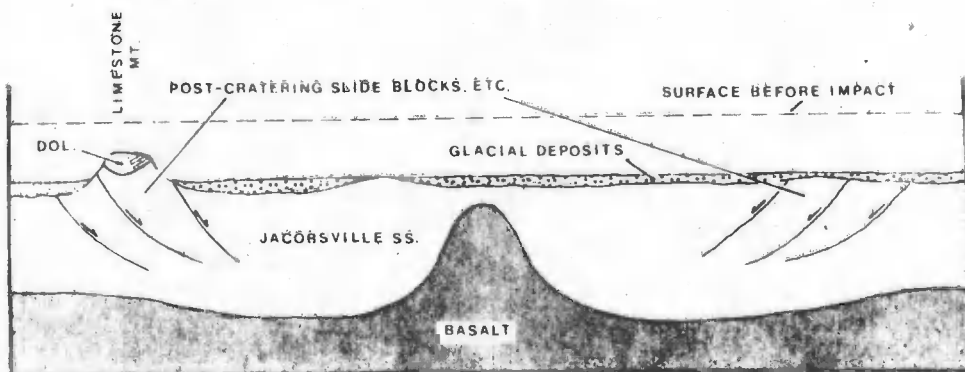


Fig. 2 Diagrammatic cross-section along a line passing through Limestone Mt. and the peak of the magnetic high shown in Fig. 1.

## THE REAPPEARANCE OF THE HURONIAN IN WYOMING

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Positive matches of all stratigraphic units through the Phantom Lake strata, Deep Lake Group and lower part of the Libby Group in Wyoming with every unit in the western part of the Huronian Supergroup in Ontario show that the two successions were originally contiguous. Recognition of this establishes an important continental sundering and subsequent reconstruction, and improves insights into environments of deposition of Paleoaphebian (earliest Proterozoic) strata in the southern part of the Canadian Shield and Wyoming structural province.

The Wyoming Province, like the Minnesota River Valley terrane, was welded onto the southern margin of the present Superior Province at 2.7 Ga. Huronian strata were deposited 2.5-2.4 Ga in an ensialic repository developed astride the boundary between the two future structural provinces. Deposition was controlled by syn-depositional faulting and warping accompanying uplifts in regions to the east, north, and west as well as by superimposed effects of glacial loading and unloading and sea level changes. Some enigmatic granite bodies were intruded at 2.4 Ga.

Following intrusion of Nipissing gabbro sheets at 2.2 Ga, the continent was fragmented. The Wyoming Province fragment was split off along the Manitoulin-Niagara structural zone and rotated about 135° as indicated by foresets and other directional features in preserved remnants of the southeasterly part of the Huronian Supergroup in the Medicine Bow and Sierra Madre Mountains in southern Wyoming. The Boxelder Creek Formation in the Black Hills of South Dakota is another remnant of rafted Huronian rocks.

Younger Aphebian strata were deposited on margins of the Archean cratonic fragments, first on shelves during their post 2.2 Ga separation and later in foredeeps formed during ocean closures. They include the iron formation-bearing Marquette Range Supergroup, the fault-bounded upper part of the Libby Creek Group, rocks in the Hartville uplift, and the Estes and Roberts Draw Formations in the Black Hills. Huronian rocks were folded and metamorphosed along with these younger strata during 1.9-1.8 Ga collisions with island arc terranes to the south, resulting in the preservation of remnants of both sets of strata of disparate age and character on the north sides of the Niagara-Manitoulin zone and the Cheyenne tectonic zone.

## Review of Analytical Methods for the Determination of Platinum Group Elements

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PGE's (platinum group elements: Pt, Pd, Rh, Ru, Ir, Os) present analytic difficulties due to low natural background levels in rocks (Pt and Pd: 10 ppb; Ru: 0.1 ppb). The insolubility of the pure metals in common acids and the ease with which Ru and Os oxidize to volatile species present additional difficulties which, when ignored, lead to low recoveries of Os and Ru (Van Loon, 1984). Steps which must be considered in any PGE analysis include: 1) sample decomposition, 2) separation of the PGE's from the products of the sample decomposition, and 3) quantitative determination of concentration. The following survey of analytical techniques is presented to provide a guide to the current literature.

### Sample decomposition techniques

The major elements in PGE-bearing rocks can be readily brought into solution with **conventional acid** techniques such as HF-aqua regia dissolution. However, little data exists on the solubility of major platinum group minerals such as sulfides and arsenides. Reported analyses for Pt and Pd on standard reference materials using acid digestion usually are low (Hall and Bonham-Carter, 1988), and Os and Ru are generally lost as volatile tetroxides unless distillation procedures are employed. **Chlorination** can be used to decompose samples by passing dry chlorine over a mixture of the sample with NaCl and activated C (Westland, 1981; Dolezal et al., 1966). The volatilized metals are absorbed in HCl, resulting in soluble PGE-chlorides. Decomposition can also be achieved with **oxidizing fusions** using Na and K carbonate or hydroxide, Na<sub>2</sub>O<sub>2</sub>, borax or boric oxide, Li tetraborate or metaborate, K pyrosulfite, or the alkaline fluorides (Johnson and Maxwell, 1981). Such fusions may suffer from slow attack on PGE's (Westland, 1981), and may also result in loss of Os and Ru.

The **reducing fusion (classical lead fire assay)** serves two functions: decomposition and PGE separation. The fusion produces a two phase, Pb°-slag system in which the PGE's are distributed into the Pb°. Upon oxidation (cupellation) to remove the Pb, the PGE's are left in a purified metallic state, although loss of Os, Ir, and Ru occurs. Any number of determination methods can be used on the bead. Detailed accounts of the Pb assay method are given in Beamish and Van Loon (1977) and Haffty et al. (1977). To overcome the limitations of the Pb fire assay, a collection method similar to **matte smelting** was developed (the **nickel sulfide fire assay**; Robért et al., 1971; 1972). The sample is decomposed and the PGE's are distributed into the sulfide phase. This method has proven equal to or better than collection using Pb. Among the advantages of a NiS collector are:

- smaller charge to sample ratio
- lower fusion temperature
- collection of all PGE's with no pretreatment for high S samples as in the lead method, and
- no change in charge composition required for different samples, except for chromite ores.

The PGE's are separated from the NiS using HCl and are determined by neutron activation analysis (NAA) (all PGE's), or are dissolved in aqua regia and determined by emission, absorption or mass spectrometry (Pt, Pd, Rh). Recent advances in this method include the reduction of collector mass to as little as 0.5 gram without affecting element recovery (Asif and Parry, 1989).

## Separation techniques

In the Pb fire assay, Ag is separated from Au, Pt and Pd by nitric acid. In the NiS fire assay, the PGE's are separated from the nickel sulfide by dissolution of the button in HCl; the PGE sulfides are filtered and their concentration determined. Any PGE's lost due to dissolution into HCl can be recovered by **coprecipitation** with Te (Shazali et al., 1987). Os and Ru can be separated from complex solutions and from each other using **distillation**. The tetroxides are collected in reducing or alkaline solutions, or in hydrogen peroxide (Beamish and Van Loon, 1977; Walker, 1988). Koster & Schmuckler (1967) synthesized **chelating ion exchange resins** which strongly bind PGE's and Au but not base metals. This method involves acid dissolution of the sample, binding of a PGE-hydroxy-chloride complex to the resin, and elution (Warshawsky et al., 1980). A variety of determination methods can be applied. Nadkarni and Morrison (1974) used an ion exchange resin to separate PGE's from samples already activated with neutrons; the resin with adsorbed PGE's was counted to determine PGE concentrations. Potential loss of PGE's during dissolution and incomplete elution of PGE's from the resin may hamper PGE analysis using resins. **Liquid-liquid extraction** methods are undergoing intensive research for both analytical and extractive purposes (Warshawsky, 1983), but routine laboratory methods for PGE determination are not yet common.

## Determination techniques

The variety of analytical techniques available to determine PGE's has increased since Crocket and Cabri's (1981) review of PGE analytical methods. Graphite furnace atomic absorption spectrometry (GF-AAS), inductively coupled plasma emission spectrometry (ICP-ES), and direct current plasma emission spectrometry (DCP-ES) are currently widely used for the determination of Pt, Pd, and Rh, usually on samples from which PGE's have been separated and concentrated. The trend in determinative techniques is toward neutron activation analysis (NAA) and inductively coupled plasma-mass spectrometry (ICP-MS). A comparison of current techniques can be found in Hall and Bonham-Carter (1988).

NAA is widely used for determination of all six PGE's at low concentrations (Hoffman, et al., 1978; Shazali et al., 1987). Decomposition and separation steps are usually employed to increase sensitivity and reduce interferences; these include the Pb and NiS fire assay techniques, ion exchange resins and distillations. The sample is bombarded with neutrons, and the intensities and wavelengths of any radioactive daughter elements produced are measured. Quantitative determination is made by comparison with standards. Recent advances in this method include the direct determination of Rh with no preconcentration using 38 MeV alpha particles (Volfinger, 1989).

A review of the technique of ICP-MS can be found in Houk and Thomson (1988), and its application to PGE determination is described in Date et al. (1987) and Gregoire (1988). The decomposed sample is introduced as a fluid usually via a nebulizer to a plasma in which atomization and ionization occur. The ions are conducted to a quadrupole mass analyser. The technique affords excellent sensitivity, linear dynamic range and multi-element capability. Determination of Pt, Pd, and Rh using fire assay preconcentration is already a standard technique. As usual, precautions in the decomposition step must be taken when analyzing for Os and Ru. Techniques such as isotope dilution have been developed for determination of Pt and Os on the ICP-MS (Date et al., 1987).

## REFERENCES

- Asif, M and Parry, S.J., 1989, Elimination of reagent blank problems in the fire-assay pre-concentration of the platinum group elements and gold with a nickel sulfide bead of less than one gram mass, *Analyst*, v. 114, pp. 1057-1059.
- Beamish, F. E. and Van Loon, J. C., 1977, *Analysis of Noble Metals*, Academic Press, N.Y.
- Crocket, J.H. and Cabri, L.J., 1981, Analytical methods for the platinum-group elements, in Cabri, L.J., ed., *Platinum-Group Elements: Mineralogy, Geology, Recovery*, Can. Inst. Mining Metall. Spec. Pub. 23, pp. 71-82.
- Date, A.R., Davis, A.E. and Cheung, Y.Y., 1987, The potential of fire assay and inductively coupled plasma source mass spectrometry for the determination of platinum group elements in geological materials, *Analyst*, v. 112, pp. 1217-1222.
- Dolezal, J., Povondra, P., and Sulcek, Z., 1966, *Decomposition Techniques in Inorganic Analysis*, American Elsevier Publ. Co., Inc., N.Y., 224 pp.
- Gregoire, D.C., 1988, Determination of platinum, palladium, ruthenium, and iridium in geological materials by inductively coupled plasma mass spectrometry with sample introduction by electrothermal vaporization, *J. Anal. Atom. Spectrom.*, v. 3, pp. 309-314.
- Haffty, J., Riley, L. B., and Goss, W. D., 1977, A manual on fire assaying and determination of the noble metals in geological materials, *U.S.G.S. Bull.* 1445, 58 pp.
- Hall, G.E.M. and Bonham-Carter, G.F., 1988, Review of methods to determine gold, platinum and palladium in production oriented geochemical laboratories, with application of a statistical procedure to test for bias, *J. Geochem. Explor.*, v. 30, pp. 255-286.
- Hoffman, E.L., Hancock, R., Naldrett, A.J., Van Loon, J.C., Hancock, R.G.V. and Manson, A., 1978, The determination of all the platinum group elements and gold in rocks and ores by neutron activation analysis after preconcentration by a nickel sulfide fire assay technique on large sample size, *Anal. Chim. Acta*, v. 102, pp. 157-176.
- Houk, R.S. and Thomson, J.T., 1988, Inductively coupled mass spectrometry, *Mass Spectrom. Rev.*, v. 7, pp. 425-461.
- Johnson, W.M. and Maxwell, J.A., 1981, *Rock and Mineral Analysis*, 2nd ed., John Wiley and Sons, 489 pp., N.Y.
- Koster, G. and G. Schmuckler, 1967, Separation of noble metals from base metals by means of a new chelating resin, *Anal. Chim. Acta*, v. 38, pp. 179-184.
- Nadkarni, R.A. and Morrison, G.H., 1974, Determination of the noble metals in geological materials by neutron activation analysis, *Anal. Chem.*, v. 46, pp. 232-236.
- Robért, R. V. D., van Wyck, E., Palmer, R., 1971, Concentration of the noble metals by a fire-assay technique using nickel sulfide as the collector, *N.I.M. Report* 1371, 14 pp.
- Robért, R. V. D., van Wyck, E., Palmer, R., and Steele, T.W., 1972, The development of a fire-assay procedure using nickel sulphide as the collector for the noble metals, *Journal of the South African Chemical Inst.*, v. 25, pp. 179-189.
- Shazali, I., Van't Dack, L., and Gijbels, R., 1987, Determination of precious metals in ores and rocks by thermal neutron activation/gamma-spectrometry after preconcentration by nickel sulphide fire assay and coprecipitation with tellurium, *Anal. Chim. Acta*, v. 196, pp. 49-58.
- Van Loon, J.C., 1984, Accurate determination of the noble metals I. Sample decomposition and methods of separation, *Trends in Anal. Chem.*, v. 3, pp. 272-275.
- Volfinger, M., 1989, Determination of rhodium in geomaterials by high-energy alpha-particle activation, *J. Radioan. Nucl. Chem., Articles*, v. 131, pp. 19-35.
- Walker, R.J., 1988, Low-blank chemical separation of rhenium and osmium from gram quantities of silicate rock for measurement by resonance ionization mass spectrometry, *Anal. Chem.*, v. 60, pp. 1231-1234.
- Warsawsky, A., Fieberg, M.M.B., Mihalik, P., Murphy, T.G. and Y.B. Ras, 1980, The separation of Platinum group metals (PGM) in chloride media by isothiourium metals, *Separation and Purification Methods*, v. 9, pp. 209-265.
- Warsawsky, A., 1983, Integrated ion exchange and liquid-liquid extraction process for the separation of platinum group metals (PGM), *Separation and Purification Methods*, v. 11, 95-130.
- Westland, A.D., 1981, Inorganic chemistry of the platinum-group elements, in Cabri, L.J., ed., *Platinum-Group Elements: Mineralogy, Geology, Recovery*, Can. Inst. Mining Metall. Spec. Pub. 23, pp. 5-18.

## Structural studies in the Huron Bay Parautochthon, Upper Michigan.

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The Huron Bay Parautochthon, located between the Huron Mountains and Keweenaw Bay in Baraga County, Upper Michigan, is a belt of strained Proterozoic metasediments bound by the Jacobsville sandstone to the north and Archean Gneisses to the east and south (fig. 1). This belt of deformed metasediments belongs to the Upper Slate Member of the Michigamme Formation. It consists of a thin sequence of shelf sediments overlain by a thick sequence of slates and discontinuous psammitic units. Early work in the region by Klasner (1978) showed at least four generations of foliation and three tectonic lineations exist as a result of the 1.9 Ga Penokean orogeny. Recent studies by Dyke (1988), Sikkila (1987), and Van Rosendaal (1985) in the area formerly known as the Baraga basin have documented a thrust/fold belt characterized by multiple generations of imbricate thrusting associated with northward verging folds. A prominent change in the structural style and amount of finite strain was shown by Gregg (1989) to mark the existence of an east-west trending thrust fault near the village of L'Anse. This large scale

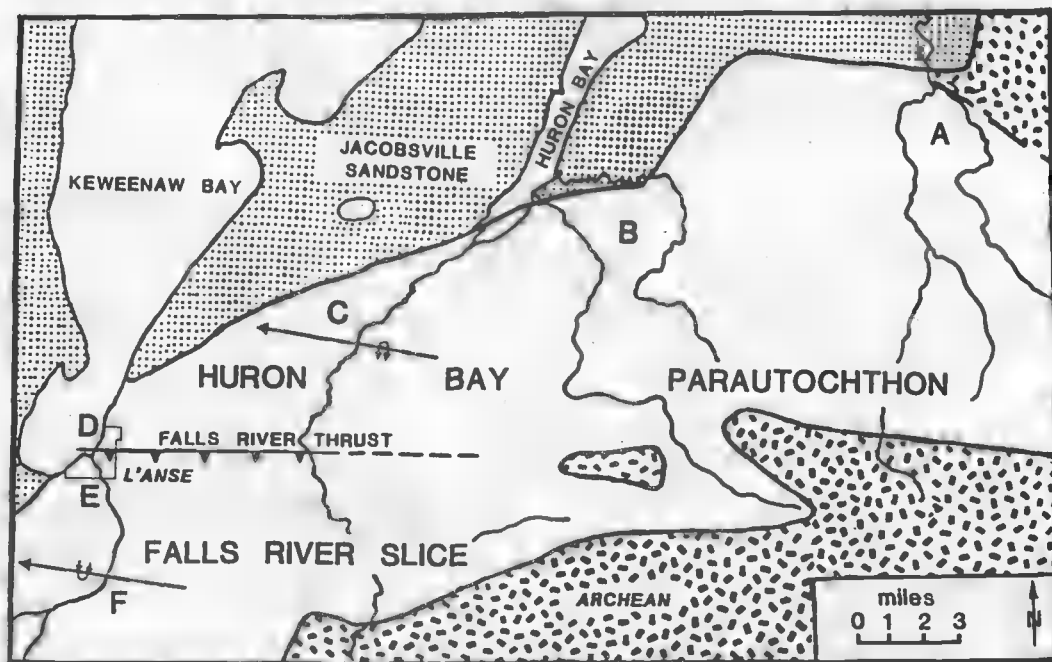


Figure 1: Generalized geologic map of the Huron Bay Parautochthon. A - Huron River, B - Slate River, C - Silver Falls Anticline, D - Keweenaw Bay, E - Falls River, F - Little Mountain Syncline.

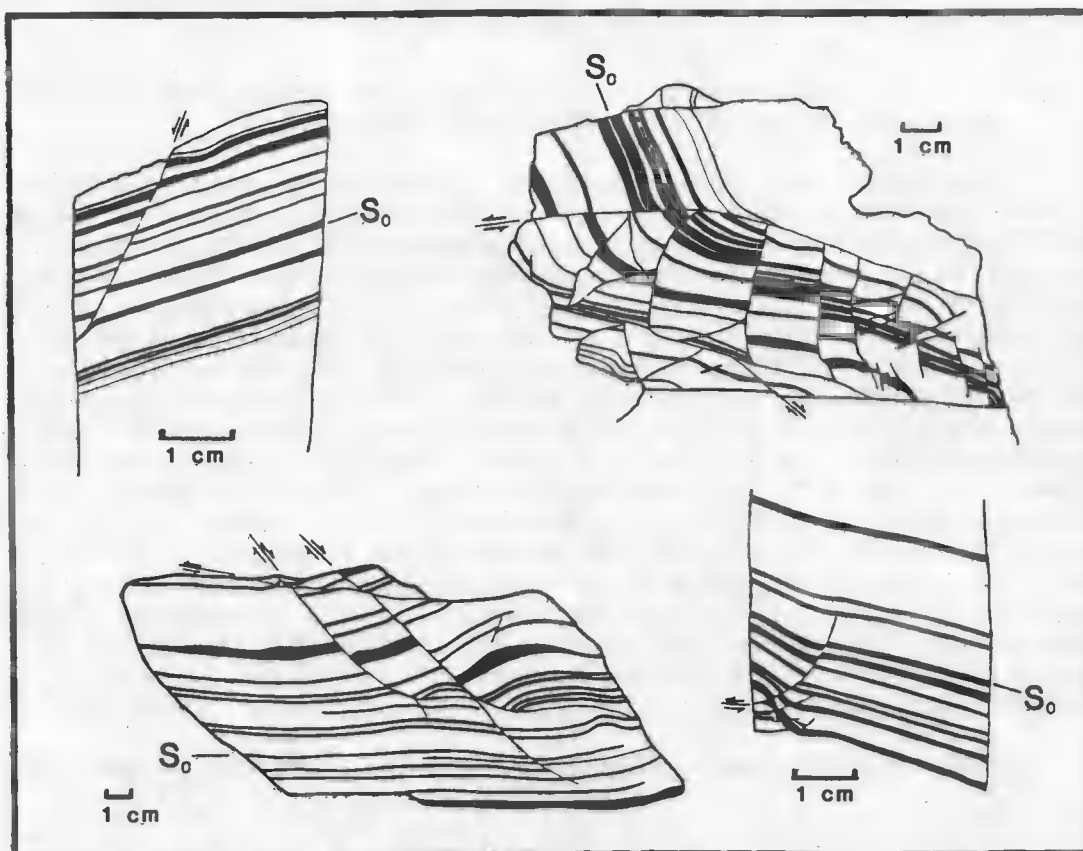


Figure 2: Faults viewed normal to the plane of cleavage.

discontinuity, known as the Falls River Thrust, separates the Baraga Belt into two previously unrecognized structural domains, the Huron Bay Parautochthon to the north, and the autochthonous Falls River Slice to the south (fig. 1).

Throughout the Huron Bay Parautochthon, rocks of the upper slate member display only one structural style group. Generally characterized by B<sub>1</sub> folds with S<sub>1</sub> cleavage, this style group is overprinted by small post-kinematic low angle thrust faults. B<sub>1</sub> folds display shallow axial plunges to northwest and southeast, and axial planes that dip to the southwest from 45 to 60 degrees. Fold profiles vary from open to gentle folds with amplitudes of less than 2 meters in the north-central and northeast parts of the parautochthon (areas A and B on fig. 1), to high amplitude tight folds along the south west section (area C of fig. 1). S<sub>1</sub> slaty cleavage is defined by anastomosing, continuous mica films of neomineralized white mica, with bedding-parallel fine detrital layer silicates and opaque minerals in the intervening quartzo-feldspathic microlithons. Large chorite-white mica aggregates with (001) traces parallel to bedding occur commonly within the microlithons and have strain shadows parallel to S<sub>1</sub>, a feature which distinguishes S<sub>1</sub> from other foliations present in

the allochthonous Falls River Slice. The length of the strain shadows increases from east to west in the parautochthon, and from north to south across the Falls River Thrust, with increasing strain. In the eastern end of the parautochthon numerous structural domains occur, marked by small changes in the trend of  $L_1$  and in the dip of fold axial surfaces and slaty cleavage. Thrust faults striking  $N58^\circ W$  and dipping  $18^\circ$  to the south define the domains and drag bedding into a near vertical attitude. Although no second generation fabric elements are present in the area, the faults are most likely post  $B_1$  structures.

Widespread evidence of normal faulting has been observed in both the parautochthonous and autochthonous terrains. This evidence of extension, ranges in scale from outcrop size discontinuities to small slickensided surfaces a few square centimeters in area (fig. 2). Smaller fault surfaces are curvilinear to nearly cylindrical in shape. Stereo net analysis of the surfaces shows that the slickenlines are typically parallel to the cylindrical axis which itself lies in the plane of  $S_1$  cleavage. A coating of goethite, which is layered over the slaty cleavage surfaces, enhances slickensides and frequently delineates the plane of motion as it oscillates between the cylindrical fault surfaces, bedding planes, and cleavage. Further evidence of movement along the preexisting planes of cleavage is the normal offset along cleavage of a reduction spot viewed parallel to the bedding-cleavage intersection lineation. Finally, the existence of sigmoidal drag folds observed with offset laminar bedding is evidence of hard rock deformation.

#### REFERENCES

- Dyke, G.A., 1988, Structure and stratigraphy on the Silver River area, Baraga County, Michigan, (unpub. M.S. thesis), Michigan Technological University, Houghton, Michigan, 87 p.
- Gregg, W.J., 1989, Effects of large scale overthrusting on fold geometry and finite strain in the Baraga thrust/fold belt, Upper Michigan: Geol. of Michigan Symposium I. Michigan Department of Natural Resources, Lansing, Michigan, p. 14.
- Klasner, J.S., 1978, Penokean deformation and associated metamorphism in the Western Marquette Range, northern Michigan, Geol. Soc. Amer. Bull., v. 89, p. 711-722.
- Sikkila, K.M., 1987, A structural analysis of Proterozoic metasediments, northern Falls River, Baraga County, Michigan, (unpub. M.S. thesis), Michigan Technological University, Houghton, Michigan, 103 p.
- Van Rosendaal, D.J., 1985, An analysis of rock structures and strain in cleaved pelitic rocks, East Branch of the Huron River, Baraga county, Michigan, (unpub. M.S. thesis), Michigan Technological University, Houghton, Michigan, 82 p.

## GEOCHEMISTRY OF UNMINERALIZED ROCKS IN THE PARTRIDGE RIVER INTRUSION, DULUTH COMPLEX

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The Partridge River intrusion (PRI) of the Duluth Complex, northeastern Minnesota, contains a wide variety of troctolitic, gabbroic, and ultramafic rock types. Based on correlations in drill core (83 holes) and reconnaissance mapping, the PRI has been subdivided (Figure 1) into: Partridge River Troctolite Series (PRTS), Partridge River Gabbro Complex (PRGC), and Oxide-bearing Ultramafic Intrusions (OUI). The PRTS consists of at least eight major igneous units that are correlated in drill holes over an indicated eleven mile strike length extending (NE to SW) from the Dunka Road Cu-Ni deposit to the Wyman Creek Cu-Ni deposit (Severson, 1988; Severson and Hauck, 1990). These eight units are characterized by various troctolitic rocks and are diagrammatically portrayed in Figure 2. Most of the upper units (III-VIII) represent single cooling units in that they are floored by a bedded ultramafic member (picrite to dunite); whereas, other units near the footwall (I and II) exhibit an overall heterogeneous nature and contain abundant internal members reflecting continuous magma replenishment. Some of the units also exhibit lateral "facies" changes along strike and downcutting relationships indicating a complex intrusive history.

The PRGC is situated at the southeastern portion of the investigated area and consists of oxide-bearing gabbroic and troctolitic rocks; both locally exhibit excellent modal bedding. Portions of the PRGC were originally interpreted as a hornfelsed basalt (Colvin Creek "Gabbro", and parts of the Powerline Gabbro). However, reconnaissance mapping revealed the presence of several unusual sedimentary-like structures that are not indicative of typical North Shore Volcanic basalts, and an origin via magmatic density currents is suggested.

The OUIs are later pegmatitic intrusions consisting of dunite, peridotite, clinopyroxenite, and lesser picrite and melagabbro; all are oxide-bearing (>10%) and contain semi-massive to massive oxide horizons. These bodies are intrusive into the PRTS and include the Longnose, Longear, Section 17, Wyman Creek, and Skibo Fe-Ti prospects.

The unmineralized portions of all units were sampled (155 samples) in order to establish background geochemical levels and lithogeochemical signatures for each of the various rock units of the PRI. Whole rock, rare-earth elements, trace metals, and precious metal analyses were conducted. Background Pd, Pt, and Au values in the major rock groups average 10 ppb, 20 ppb, and 5 ppb respectively. However, slightly elevated background values are associated with Unit II (15 ppb, 24 ppb, and 9 ppb respectively), and the OUI rock group (15 ppb, 24 ppb, and 17 ppb respectively). In the course of sampling unmineralized rock (<1% sulfides), five anomalous samples (>200 ppb combined Pd and Pt) were revealed with a maximum of 910 ppb. The OUI units are the most geochemically

unique in that they have elevated background values for  $\text{TiO}_2$ , V, Cr, Co, Cu, Cd, C, Be, Sc, Pb, Te, Au, and W relative to the other igneous rocks of the Partridge River intrusion.

Geochemical data (whole rock, REE) support the breakdown of the various rock units identified within the Partridge River intrusion. Several X-Y plots and spider diagrams have been constructed and show a definite clustering of specific rock units, and within each of the major igneous rock units some specific rock types also show clustering (the MG-Number plot depicted in Figure 3 is one example). For instance, Units I and II exhibit a markedly different geochemical signature when compared to the other PRTS units. One interpretation of this difference is that magma contamination due to assimilation of footwall material was important in their genesis. The lower half of Unit I, which contains the most hornfels inclusions, demonstrates a markedly different geochemical signature when compared to the other PRTS units. The basal ultramafic horizons within the PRTS all cluster together and represent the most primitive rock type sampled. All rock units of the PRGC exhibit a different geochemical signature, which, in turn, is similar to the geochemical signature for the lower half of Unit I. The OUI units exhibit a markedly different geochemical signature when compared to the PRTS ultramafic horizons and to all the other PRI units.

Severson, M.J., 1988, Geology and structure of a portion of the Partridge River intrusion: a progress report: Technical Report NRRI/GMIN-TR-88-08, Duluth, Minnesota, 78 p.

Severson, M.J., and Hauck, S.A., 1990, Geology, geochemistry, and stratigraphy of a portion of the Partridge River Intrusion: Technical Report NRRI/GMIN-TR-89-11, Duluth, Minnesota, 236p.

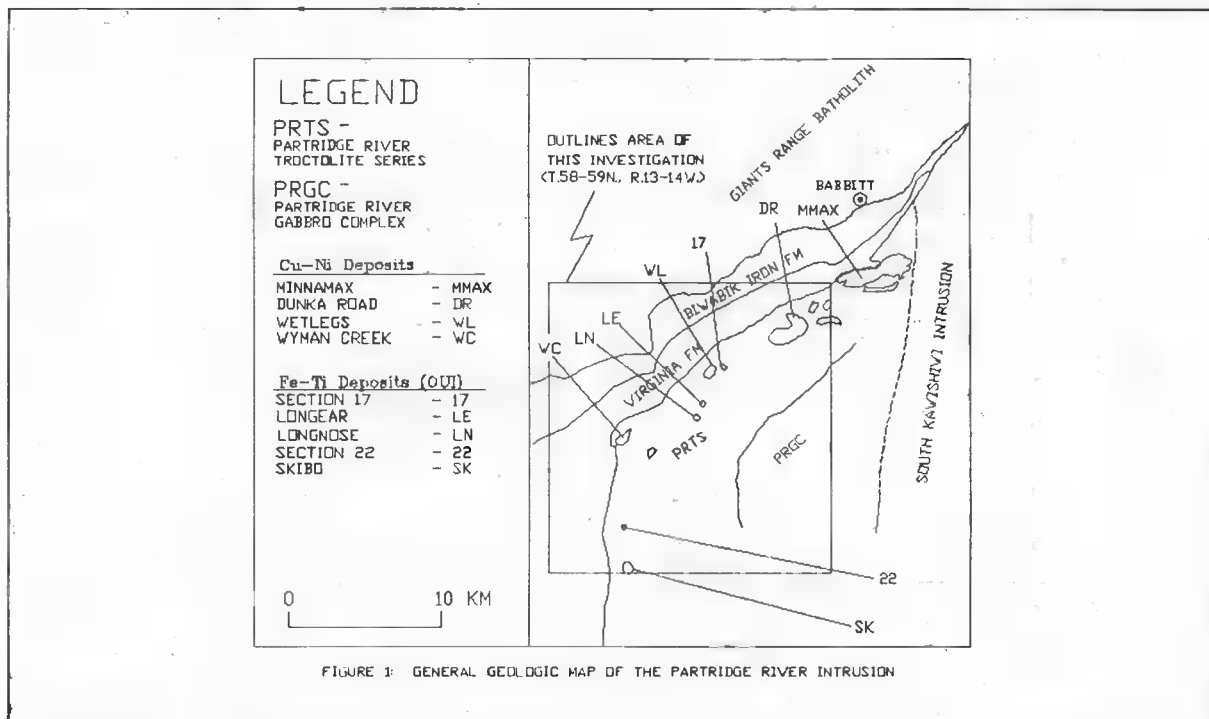
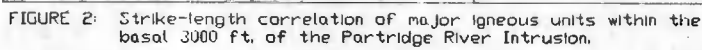
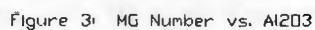


FIGURE 1: GENERAL GEOLOGIC MAP OF THE PARTRIDGE RIVER INTRUSION

23<sup>6</sup> MOLEY

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

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



## The Great Lakes tectonic zone--A major north-verging Late Archean collision zone

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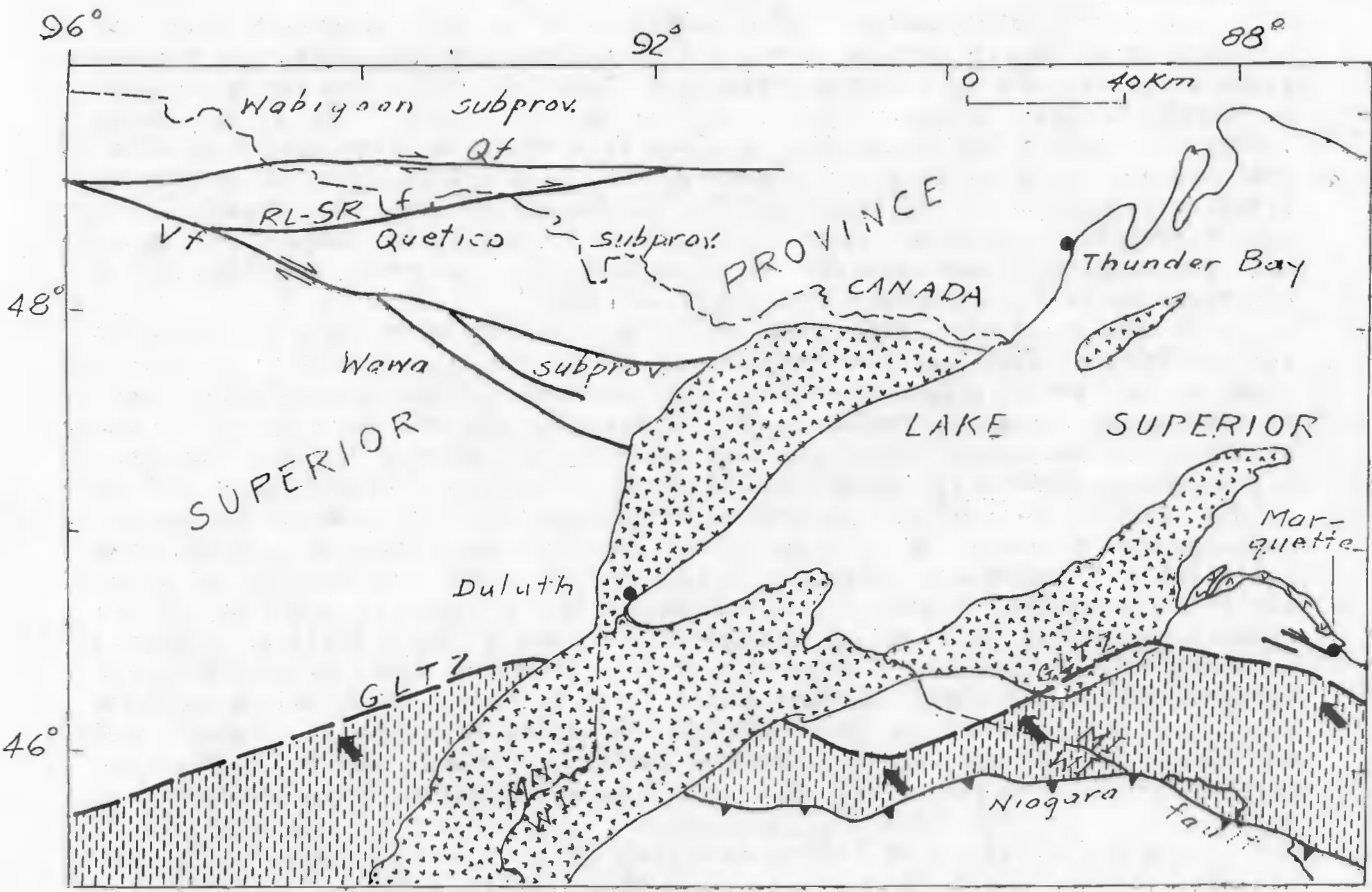
The Great Lakes tectonic zone (GLTZ) is an Archean crustal boundary of subcontinental length that separates a Late Archean greenstone-granite terrane (Wawa subprovince of the Superior province, Canadian Shield) on the north from an Early to Late Archean gneiss terrane on the south. It is generally interpreted as a paleosuture that resulted from continent-continent collision. The tectonic zone is covered at most places in the Lake Superior region by Proterozoic rocks or Pleistocene glacial deposits, and its position and characteristics previously have been determined mainly by geophysical data. Geologic mapping in the Marquette, Michigan area (Sims, in press) provides direct observations of the structure for the first time.

In the Marquette area, the GLTZ is a 2.4-km-wide zone of mylonite (orthomylonite) that has been superposed on predominantly massive granitoid rocks of the Archean greenstone-granite terrane and on previously deformed rocks of the gneiss terrane. Foliation in the mylonite strikes about N. 60° W. and dips steeply southwest, subparallel to the boundary between the two terranes. A pronounced stretching lineation and tight fold hinges plunge about 45° S. 45° E. The attitude of the stretching lineation (line of tectonic transport) together with asymmetric structures indicative of sense of movement indicate that collision in the Marquette area was oblique and resulted in dextral-thrust shear along the boundary, northwestward vergence, and probable overriding of the greenstone-granite terrane by the gneiss terrane. This implies southward subduction of the greenstone-granite terrane. Transmittal of the dextral shear stress across a large area of the Superior province crust to the north may have been responsible for the nearly east-west foliation, upright folds, and northwest- to east-west-trending dextral faults and shear zones at least as far north as the Quetico fault (Qf, fig. 1), in southern Ontario, a distance of about 250 km.

As a whole, the GLTZ is characterized by systematic angular bends that alternately trend west-northwestward, as in the Marquette area, and northeastward (fig. 1). This zigzag pattern probably reflects original irregularities in the continental margin (Superior province). Late Archean convergence along this margin resulted in a variable trajectory of stress northward into the greenstone-granite crust and probably in along-strike diachroneity of orogeny. The major deformation was caused by oblique compression at promontories, which acted as buttresses against which compressive stress was directed into the crust. In addition to the dominant foliation and upright folds, major brittle-ductile to brittle strike-slip faults, such as the Vermilion fault system (Vf, fig. 1) in northern Minnesota and the Quetico and Rainy Lake-Seine River faults (RL-SRf, fig. 1) in southern Ontario, resulted from a more brittle continuum of the transpressive shear caused by collision along the GLTZ. Precise isotopic ages (Davis and others, 1989) suggest that the collision occurred at about 2,690 Ma.

### References

- Davis, D.W., Poulsen K.H., and Kamo, S.L., 1989, New insights into Archean crustal development from geochronology in the Rainy Lake area, Superior Province, Canada: *Journal of Geology*, v. 97, p. 379-398.
- Sims, P.K., in press, Great Lakes tectonic zone in Marquette area, Michigan--Implications for Archean tectonics in north-central United States: U.S. Geological Survey Bulletin 1904-E.



Geologic map of Precambrian rocks, north-central United States

EXPLANATION

- |                                                                                     |                                              |
|-------------------------------------------------------------------------------------|----------------------------------------------|
| MIDDLE PROTEROZOIC                                                                  |                                              |
|  | Rocks of Midcontinent rift system            |
| EARLY PROTEROZOIC                                                                   |                                              |
|  | Wisconsin magmatic terranes (1,860-1,889 Ma) |
| ARCHEAN                                                                             |                                              |
|  | Greenstone-granite terrane (2,680-2,750 Ma)  |
|  | Gneiss terrane (2,600-3,600 Ma)              |
|  | Direction of tectonic transport              |

Geologic Significance of Linear Features  
Visible on Landsat Images in West-central Minnesota

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The geologic significance of linear features visible on Landsat images can be assessed by integration with several data sets. Observations of linear features on four Landsat images in west-central Minnesota are compared with aeromagnetic maps and the resulting data set is then compared with: 1-published interpretations of faults in Precambrian crystalline rocks, 2-concentration of radon in groundwater, and 3-water well records. It appears that linear features visible on Landsat, in places correspond with fault zones in Precambrian crystalline rocks and that these basement faults have influenced fluid movement and Mesozoic weathering patterns.

Images employed in this study are standard EROS produces at scales of 1:1,000,000 (film positives) and 1:250,000 (paper) and were provided by a grant from the Minnesota Geological Survey. Linear features were mapped on the multispectral scanner images in bands 2 and 4, compiled on an uncorrected mosaic, and compared with aeromagnetic maps (Fig. 1). Individual linear features observed on both bands are virtually all parallel to linear aeromagnetic anomalies. These linear features are believed to be most significant and form the basis for the interpretation of lineament zones which are corridors of linear-feature concentration separating large areas with different linear-feature orientation. Lineament zones correspond with Precambrian convergent margins and with fault zones trending oblique to the margins (Shurr and Watkins, in press). However, it is the geologic significance of individual linear features which is assessed in this current study.

Specific linear features and faults in Precambrian crystalline rocks are shown in Figure 2. In addition to linear features shown in Figure 1, some linear features from the original data set (viz., bands 2 or 4) are included in Figure 2 where they parallel a fault. Published faults or fault zones which are marked by Landsat linear features include: 1-the Serpent Lake and Malma structural discontinuities (1-A and 1-B, respectively) (Southwick and others, 1988); 2-the Great Lakes Tectonic Zone (Sims and others, 1980); 3-the Appleton geophysical lineament (Southwick and others, 1989); 4-a basement fault near Renville (4-A) (Southwick and others, 1989) and a fault bounding a Precambrian depositional basin (4-B) (Southwick and Mossler, 1984); 5-two paired, parallel faults bounding Precambrian basins (5-A and 5-B) (Southwick and Mossler, 1984); and 6-faults bounding the Nimrod outlier and Long Prairie basin (6-A and 6-B, respectively) (Southwick and others, 1988). These major fault zones correspond with lineament zones and individual faults within the zones are marked by specific linear features.

In southwest Minnesota, contour maps summarizing radon concentrations in groundwater show patterns corresponding with Landsat linear features. Near Jeffers (J, Fig. 2), an area of high radon activity in groundwater (Southwick and Lively, 1984) lies along a fault zone mapped in Precambrian quartzite (Southwick and Mossler, 1984); the radon anomaly and fault zone

are marked by a Landsat linear feature. Near Clarkfield (C, Fig. 2), contours of radon concentration in groundwater (Lively and Southwick, 1981) generally parallel the northeast trend of a basement fault zone which has expression on Landsat. Near Benson, (B, Fig. 2), radon concentrations parallel the Appleton geophysical lineament which has clear definition on Landsat. In addition, individual radon anomalies in groundwater overlie linear aeromagnetic anomalies. Radon anomalies in soil gas data have recently been related to faults in crystalline rocks in the southeastern United States (Gates and Gunderson, 1989); these data may provide an analogy for the Minnesota groundwater anomalies. In any case, there is a strong suggestion that fluids move along faults in bedrock which are marked by Landsat linear features.

In central Minnesota, geologic interpretations of water well logs provide another data base which can be integrated with Landsat observations. Near St. Cloud (SC, Fig. 1) individual linear features mapped at 1:250,000, generally parallel contours summarizing the elevation of the crystalline bedrock surface in eastern Stearns County. Linear features trending northwest and east-west outline bedrock highs and follow the trend of bedrock lows. Correlation of Cretaceous stratigraphic units shows that the bedrock lows have thick weathering residuum and probably are fault traces. The individual linear features are all components of a northeast-trending lineament zone which corresponds with an important fault zone in central Minnesota (Watkins and others, 1990).

#### REFERENCES

- Gates, A.E., and Gunderson, L.C.S., 1989, Role of ductile shearing in concentration of radon in the Brookneal zone, Virginia: *Geology*, v. 17, p. 391-394.
- Lively, R.S., and Southwick, D.L., 1981, Radon activity in groundwaters of seven test areas in Minnesota: *Minnesota Geological Survey Report of Investigations* 25, 60 p.
- Shurr, G.W., and Watkins, I., in press, Basement blocks, tectonics, and fluid movement --- "seeping" through the sedimentary cover: *Proceedings, Seventh thematic conference on remote sensing for exploration geology*.
- Sims, P.K., Card, K.D., Morey, G.B., and Peterman, Z.E., 1980, The Great Lakes tectonic zone - a major crustal structure in central North America: *Geological Society of America Bulletin*, Part I, v. 91, p. 690-698.
- Southwick, D.L., and Lively, R.S., 1984, Hydrogeochemical anomalies associated with the basal contact of the Sioux Quartzite along the north margin of the Cottonwood County basin, *in* Southwick, D.L., ed., *Shorter contributions to the geology of the Sioux Quartzite (Early Proterozoic) southwestern Minnesota*: *Minnesota Geological Survey Report of Investigations* 32, p. 45-58.
- Southwick, D.L., Morey, G.B., and McSwiggen, P.L., 1988, Geological map of the Penokean Orogen, central and eastern Minnesota and accompanying text: *Minnesota Geological Survey Report of Investigations* 37, 25 p.
- Southwick, D.L., and Mossler, J.H., 1984, The Sioux Quartzite and subjacent regolith in the Cottonwood County basin, Minnesota, *in* Southwick, D.L., ed., *Shorter contributions to the geology of the Sioux Quartzite (Early Proterozoic) southwestern Minnesota*: *Minnesota Geological Survey Report of Investigations* 32, p. 17-44.

Southwick, D.L., Schaap, B., and Chandler, V.W., 1989, Multiple Archean terranes in southwest Minnesota - the old gray gneiss she ain't what she used to be: Institute on Lake Superior Geology Proceedings, v. 35, p. 96.

Watkins, I., Shurr, G.W., and Anderson, G.G., 1990, Faults associated with the Penokean accretion of allocthanous terranes in central Minnesota: Institute on Lake Superior Geology Proceedings, v. 36.

## FIGURES

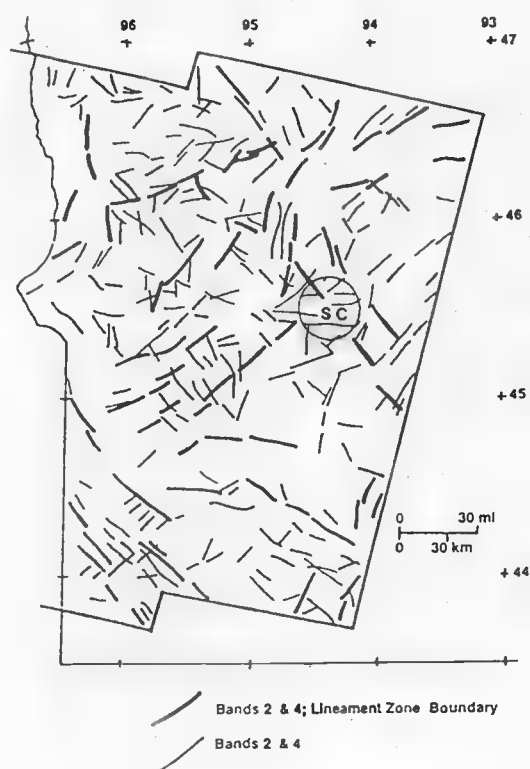


Figure 1

Linear features visible on Landsat images in bands 2 and 4 and are parallel to aeromagnetic patterns in west-central Minnesota (Shurr and Watkins, in press).

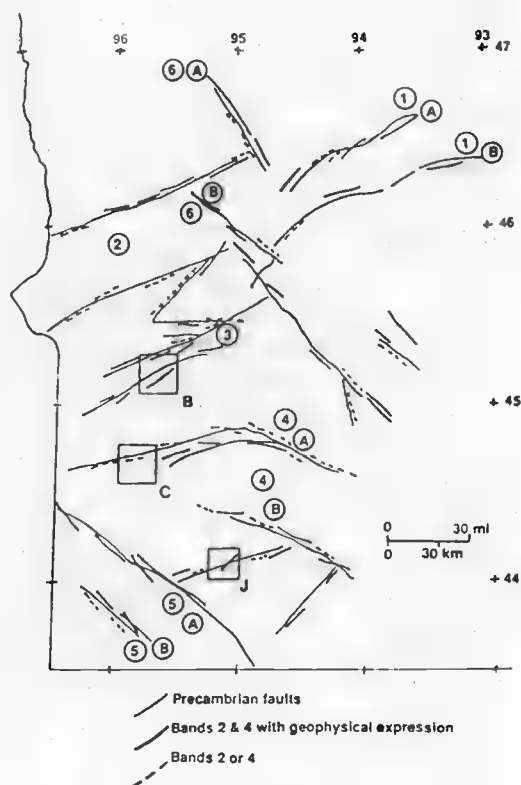


Figure 2

Correspondence of specific Landsat linear features with published structural features in the Precambrian of west-central Minnesota (Shurr and Watkins, in press). Letters refer to localities discussed in the text.

BIOTURBATION IN THE JACOBSTOWN SANDSTONE, LAKE LINDEN LOCATION -  
WHAT ARE THE IMPLICATIONS?

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Bioturbation may have been overlooked in the Jacobstown sandstone and indeed many sandstone around the world due to the size of the traces. The ichnofauna reported in this research can be observed only at the microscopic level. Petrographic examination of thin sections made from sandstone injected with blue dyed epoxy revealed patterns in porosity and permeability differing somewhat within a few centimeters. Closer examination revealed various patches in the thin section where a pattern of several grains (approximately 1 mm across) would be interrupted by a zone of mixed grains varying in diameter from .1 mm to 1 mm. These mixed grains do not appear to be from natural grain settling and they are often coated with a stain (possibly hematite). In some thin sections actual paths can be traced for approximately 1.5 cm before it becomes diffuse. In other instances the areas of mixed small and large grains (with dark coatings) may cover an area approximately 1 cm<sup>2</sup>. The thin section seems to also cut these tracings at an angle such that arcuate patches (less than 1mm across) appear. From these initial measurements, speculations could be made that an annelid type burrower that was approximately 1 mm wide was responsible. A greenish mineral resembling glauconite is also found in these thin sections along with an apparent sedimentary rock fragments (1 mm in length) that closely resembles recent annelid fecal pellets.

If these initial observations can be substantiated many of the theories of the paleogeography and tectonics of the Upper Peninsula of Michigan will be open for reinterpretation. The sands most often interpreted as fluvial, coming off of alluvial fans would change. If these are indeed ichnofauna and the greenish mineral is glauconite, these sands will have to be interpreted as marine or at least nearshore continental shelf. Cross bedded units would indicate the latter to be more likely.

The postulated presence of the ichnofauna raises many questions as to the age of these sediments which are most commonly referred to as pre Cambrian. Does this put this unit into the Cambrian or has the Ediacara fauna of the "Lost Age" in the Proterozoic been found?

## TECTONIC RAMIFICATIONS OF GNI/ARGONNE LAKE SUPERIOR SEISMIC DATA

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### ABSTRACT

Detailed bouguer gravity anomaly maps have been prepared for the Superior and Northwest Wisconsin map areas. Data collected in previous years were augmented with additional data collected during 1989.

Strong gravity gradients define the position of major Keweenaw faults. The deep gravity low over the Bayfield Peninsula abuts a strong positive gravity feature to the southwest in Bayfield County and may define a major Keweenaw cross fault or adjustment feature.

The moderate gravity low in southern Iron County corresponds to the Archean Puritan batholith and helps to define relations to Proterozoic metavolcanic and metasedimentary rock to the south.

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Advances in geochronology of the Michipicoten greenstone belt.

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New U-Pb zircon ages for the Wawa area enlarge the existing data base of ages for this belt. The existence of four volcanic cycles is now well documented. The association of volcanism and plutonism continues to be confirmed. There is no difference, in terms of ages, between the internal and external plutons. The internal being those that are within the supracrustal rocks while external are those surrounding and embaying the greenstone belt.

The Michipicoten belt was formed by several volcanic cycles and plutonic events over a protracted period of time, that can be divided into six events as shown in the tabulation below. The oldest event is dated by a granite, a porphyry, and a volcanic at ca. 2888 Ma. The next cycle of volcanism and associated plutonism was at ca. 2743 Ma. The Alden volcanic tuff has been dated at  $2746 \pm 15$  Ma, the Jubille felsic volcanic at  $2747 \pm 11$  Ma and the Jubille porphyry at  $2742 \pm 6$  Ma. The Goodreau volcanic center yields an age of  $2729 \pm 3$  Ma. and belongs either here or in Event III at ca. 2717 Ma. Event IV has been well defined by volcanic and plutonic rocks at ca. 2696 Ma. The age obtained for the McCormic Lake tuff at  $2701 \pm 8$  Ma can be assigned to this event. New ages that fit into Event V are:  $2686 \pm 13$  Ma for the Dubreuilville external granite, the internal granite at Dickenson Lake at  $2673 \pm 8$  Ma. and the Lund Lake granitic stock at  $2663 \pm 6$  Ma. The youngest event at 2615 Ma is thought to pertain to a tectonic event in the region.

The new ages reported here conform to the established pattern of ages in the area. Also, they are in good agreement with ages for other nearby greenstone belts, with the exception of the 2888 Ma event which has not been identified in them. It appears that the Michipicoten belt evolved in ca. 220 Ma. Moreover, it seems that volcanism, much of the associated sedimentation, and plutonism, is essentially synchronous, or coeval in the evolution of a greenstone belt, rather than sequential. Obviously a cogenetic relation between volcanics and plutonics is likely. It is also clear that the external granitoid terranes of batholithic dimensions formed by multiple intrusions over ca. 220 Ma.

Zircon Ages for the Michipicoten greenstone belt  
(Wawa, Gamitagama, Michibishu).

|            |      | EXTERNAL | INTERNAL |           |
|------------|------|----------|----------|-----------|
| EVENT (Ma) |      | PLUTONS  | PLUTONS  | VOLCANICS |
| VI ca.     | 2615 | 2615     |          |           |
| V          |      | 2662     | 2662     | 2677      |
|            |      | 2671     | 2663     |           |
| ca.        | 2668 | 2673     | 2668     |           |
|            |      | 2675     | 2668     |           |
|            |      | 2686     | 2673     |           |
|            |      |          | 2685     |           |
| IV         |      | 2693     | 2702     | 2696      |
|            |      | 2694     |          | 2698      |
| ca.        | 2696 | 2696     |          | 2691      |
|            |      | 2698     |          | 2701      |
|            |      | 2698     |          |           |
| III ca     | 2717 | 2721     | 2722     | 2713      |
| II         |      | 2747     | 2737     | 2729      |
| ca.        | 2743 |          | 2742     | 2744      |
|            |      |          | 2745     | 2746      |
|            |      |          |          | 2747      |
| I ca.      | 2888 | 2881     |          | 2889      |
|            |      | 2888     |          |           |

Note: Ages in above tabulation are as reported here plus as reported and compiled by:  
Turek A., Keller R., Van Schmus W.R., (1990). The age of volcanism and plutonism in the Mishibishu greenstone belt near Wawa, Ontario. Canadian Journal of Earth Sciences 27, 5 (in press).

# THE GEOLOGY OF THE GREENWOOD LAKE AREA DULUTH COMPLEX, LAKE COUNTY, NORTHEASTERN MINNESOTA

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The dominant feature in the Greenwood Lake area is the Greenwood Lake (or "Snake") Anomaly. This positive magnetic anomaly within the troctolitic series of the southern Duluth Complex was previously described by Vadis and others (1981). Geologic mapping at 1:24,000 scale during the summer of 1989 of four 7.5' quadrangles (Greenwood Lake West, Greenwood Lake East, Mt. Weber, and Whyte) located previously known outcrops (Bonnichsen, 1971) as well as new outcrops, all which were sampled for petrography and geochemical analyses. The area mapped encompasses rocks of the anorthositic and troctolitic series, granophyric granite, and basalts and sediments of the North Shore Volcanic Group. A geologic map has been constructed (Figure 1) based on outcrop mapping and aeromagnetic quadrangle maps. Aeromagnetic maps were used to delineate units using magnetic trends in areas with poor to nonexistent outcrop coverage. The influence of bedrock on topography was also taken into account.

The oldest rocks are the anorthosites, gabbroic anorthosites, and troctolitic anorthosites of the anorthositic series. One NE-SW trending hill on the edge of the Toimi drumlin field has extensive outcrops of gabbroic anorthosite and anorthositic gabbro. A few isolated outcrops of troctolitic anorthosite with a distinctive spotted appearance caused by poikilitic olivines are also present. These isolated outcrops may be large xenoliths from a previous anorthositic intrusion at depth. Another smaller anorthositic body contains 1.5 - 2 cm clots of magnetite.

Intrusive into the anorthosites are rocks associated with the troctolitic series. Numerous outcrops of labradorite-augite-olivine cumulate ferrogabbro (> 10% oxides) were found along the shores of Greenwood Lake and along NE-SW trending ridges to the northwest. The ferrogabbros are all magnetic to varying degrees, and generally have weak to strong igneous lamination (foliation). Petrographic evidence indicates that magnetite was an early phase in the crystallization sequence. Subhedral to euhedral grains of titaniferous magnetite are common as inclusions in olivine, augite, and occasionally in plagioclase. Olivine is often seen rimming magnetite. The early appearance of oxides indicates that the magma was slightly enriched in oxygen.

None of the outcrops identified are believed to represent the lithology of the Greenwood Lake Anomaly itself, which can be seen on topographic maps to be completely covered by swampy terrain and Greenwood Lake. The only direct evidence of the rocks composing the anomaly are from two drill holes that intersect the anomaly. DDH S-1 (Vadis and others, 1981) only penetrated 30 feet into bedrock and intersected foliated oxide and olivine-bearing gabbros, a thin band of oxide augite troctolite, and two layers (6.5' and 3.3' thick) of feldspathic oxide peridotite. DDH MN 27015 (USX Corporation) at the south end of Greenwood Lake intersected 56' of foliated, moderately magnetic anorthositic ferrogabbro, a 4' band of strongly magnetic oxide troctolite, and then another 405' of foliated anorthositic ferrogabbro before grading into 90' of ferrogabbro with variable foliation, finally ending in oxide-bearing anorthositic gabbros. In general, the anomaly appears to be composed of layers of a variety of olivine and oxide-rich troctolitic cumulates. The relationship between the exposed foliated ferrogabbro and the adjacent

rocks of the Greenwood Lake Anomaly is not clear. The ferrogabbros are probably part of the same intrusive body as the more mafic, magnetic, and strongly foliated troctolitic rocks that compose anomaly.

Two large bodies of granophyric granite are intrusive to both anorthositic and troctolitic rocks along the eastern margin of the Greenwood Lake Anomaly. In contrast to the gabbros, the granophyre is relatively resistant and forms large hills and ridges, the best-known example of which is Mt. Weber. Felsic veins were observed in gabbros on Greenwood Lake, and a large granophyre dike cuts the magnetic basalt to the east. The granophyre is bordered to the east by magnetic basalts and at least one small basin containing a magnetic, bedded, quartz-bearing volcanic sandstone. The basalts adjacent to the granophyre are all massive, but basalts further south and away from the felsic intrusions are amygdaloidal at some locations.

Preliminary geochemical interpretations and determination of oxide compositions has begun. The results of this work will also be presented, with an evaluation of potential Platinum Group Element mineralization.

This project has been funded by the Minnesota Mineral Diversification Fund, and by the Mineral Resources Research Center.

#### References Cited

- Bonnichsen, B., 1971, Outcrop map of southern part of Duluth Complex and associated Keweenawan rocks, St. Louis and Lake Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map Series M-11, scale 1:125,000.
- Vadis, M. K., Gladen, L. W., and Meineke, D. G., 1981, Geological, geophysical and geochemical surveys of Lake, St. Louis and Cook counties, Minnesota for the 1980 drilling project: Hibbing, Minnesota, Minnesota Department of Natural Resources, Division of Minerals, Report 201, 13 p.

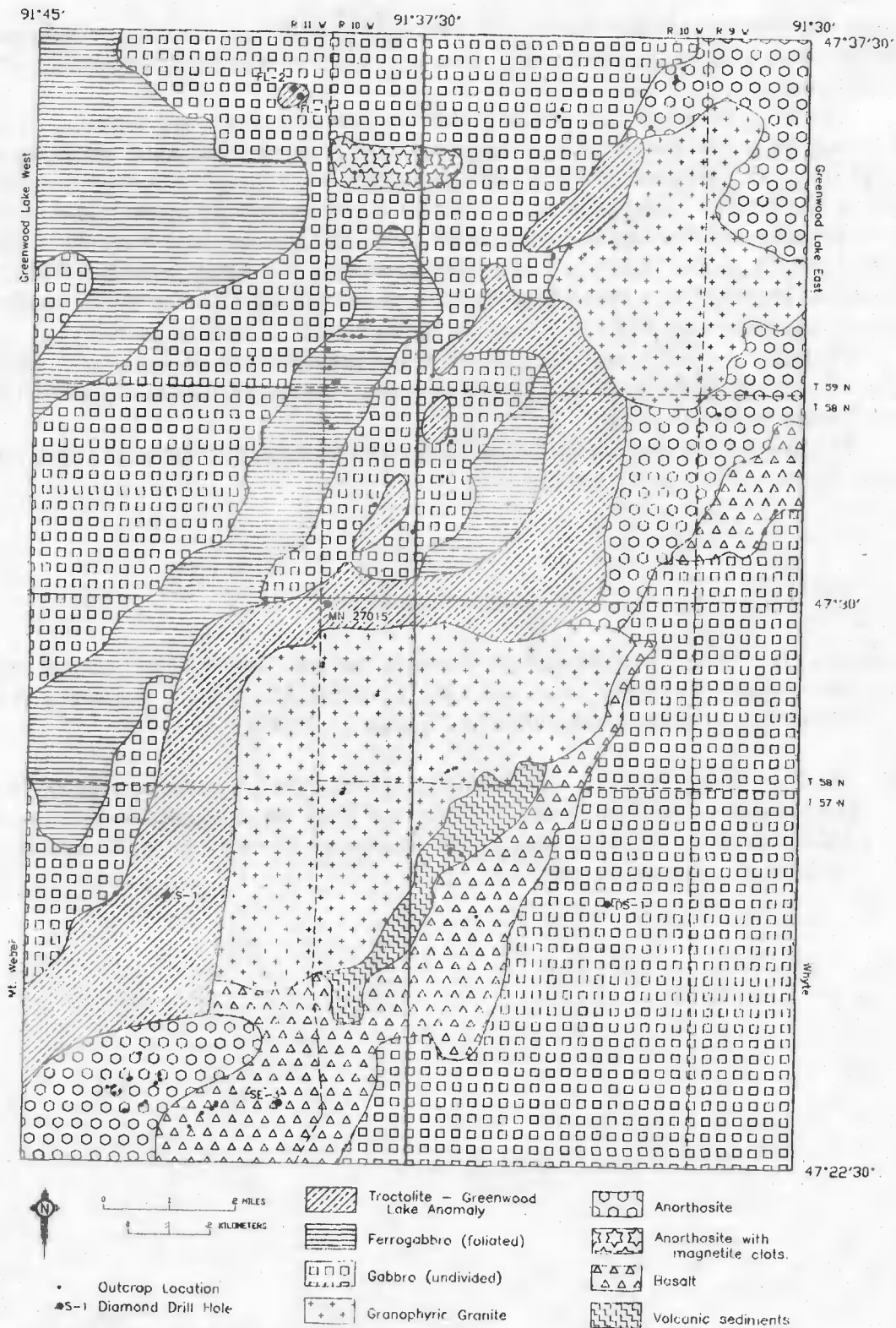


Figure 1. General geology of the Greenwood Lake Area, Lake County, northeastern Minnesota.

THE MINERAL RELIEF OF SURFACES PRODUCED BY SANDING WITH QUARTZ  
PERCUSSION, THERMAL DISAGGREGATION, AND WEATHERING

by

Denise Victory and Ivan Watkins

We have hypothesized that the processes which archaeological stonemasons used when working stone left surfaces that could be used to identify the process used by those stonemasons. Because the minerals in a rock have different properties such as cleavage, hardness, coefficient of thermal expansivity, coefficient of thermal conductivity, absorption coefficients for radiant energy (color), and reactivity with water containing oxygen and hydrogen ion we were able to devise several observational tests that could be used to classify the stonemasons method of surface production. We tested our hypothesis on a sample of Reformatory Grey granite supplied to us by Cold Spring Granite Company. We produced surfaces by the methods that archaeologists have suggested for Peruvian stone works. In Table 1 the relative mineral relief we observed for each surface is tabulated with the process used to produce the surface.

The logical conclusions from the table are that, if an archaeologist were educated to look for the mineral relief of a surface, that archaeologist would be able to determine the process the ancient stonemasons used to produce the artifacts which are found today. There are no processes we used on the grey granite that can not be distinguished from all of the other processes. Of course it is possible to hypothesize two or more processes being used by the stonemasons to produce the surface. However, if hammering or wedging and sanding with quartz are combined, the result is the same as just sanding with quartz.

Table 1

| PROCESS                                | SURFACE MINERAL RELIEF                                                                                                          |                               |                             |                                |                              |                                 |
|----------------------------------------|---------------------------------------------------------------------------------------------------------------------------------|-------------------------------|-----------------------------|--------------------------------|------------------------------|---------------------------------|
|                                        | quartz<br>vs<br>biotite                                                                                                         | quartz<br>vs<br>hornblende    | quartz<br>vs<br>feldspar    | mica<br>vs<br>hornblende       | mica<br>vs<br>feldspar       | feldspar<br>vs<br>hornblende    |
| HAMMERING<br>OR<br>WEDGING             | There was no pattern. Any mineral could stand above any other. The cleavage surfaces of all minerals in the rock were observed. |                               |                             |                                |                              |                                 |
| SANDING<br>WITH<br>QUARTZ              | quartz<br>above<br>biotite                                                                                                      | quartz<br>above<br>hornblende | quartz<br>above<br>feldspar | hornblende<br>above<br>mica    | feldspar<br>above<br>biotite | NO PATTERN<br>OBSERVED          |
| THERMAL<br>DISAGRE-<br>GATION          | biotite<br>above<br>quartz                                                                                                      | hornblende<br>above<br>quartz | feldspar<br>above<br>quartz | NO<br>PATTERN<br>OBSERVED      | biotite<br>above<br>feldspar | hornblende<br>above<br>feldspar |
| WEATHERING<br>OR ACID<br>SOLUTION      | quartz<br>above<br>biotite                                                                                                      | quartz<br>above<br>hornblende | quartz<br>above<br>feldspar | hornblende<br>above<br>biotite | feldspar<br>above<br>biotite | feldspar<br>above<br>hornblende |
| THE BIOTITE HAS BEEN WEATHERED AWAY!!! |                                                                                                                                 |                               |                             |                                |                              |                                 |

FAULTS ASSOCIATED WITH THE PENOKEAN  
ACCRETION OF ALLOCTHANOUS TERRANES IN CENTRAL MINNESOTA

by

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The theory of continental growth by docking of allocthanous terranes has now been accepted by most geologists. Plate tectonic interpretations for the Penokean orogen in the Lake Superior region have slowly been emerging in the literature over the past decade (Larue, 1983; LaBerge and Myers, 1984; Barovich and others, 1988). In central Minnesota recent reinterpretations have recognized the orogen as a convergent margin (Holst, 1984; Southwick and others, 1988; Holm and Selverstone, 1990). Since convergence is rarely perpendicular to the continental margin, accretion occurs in a transpressive regime and the geometry of the margin is reflected in the faults that are produced. The northeast trend, parallel to the continental margin, will be primarily low angle faults with dominant dip-slip and some strike-slip displacement. Faults perpendicular to margin, i.e. northwest, should be primarily subvertical with dominant strike-slip and some dip-slip displacement. The relative importance of each fault trend is determined by the angle of transpression.

The predicted fault geometries have been documented in recent mapping in the area of Mille Lacs Lake and have also been observed on several data bases farther south in the St. Cloud area. Linear features visible on satellite images at a scale of 1:1,000,000 correspond with faults mapped by other investigators (Shurr and Watkins, in press). Near Mille Lacs northeast-trending structural discontinuities dip southeast and northwest-trending faults are near vertical (Southwick and others, 1988). In the St. Cloud area, satellite linear features mark the contact between Archean gneisses and Lower Proterozoic granitic rocks. This contact and other faults have clear expression on magnetic data at scales of 1:250,000 and 1:24,000.

The fractures and faults associated with accreted terranes have magnetic lineations produced by water flux. The water provided oxygen from the atmosphere and ion transport to convert the primary magnetic mineral, magnetite, into hematite which is nonmagnetic. Magnetic anomaly maps then necessarily have a lineation parallel to the faulting. Magnetic lineation between the Archean gneisses and Proterozoic granitic rocks is obvious on aeromagnetic maps at 1:250,000 and corresponds to linear features visible on satellite images. Lenticular patterns on 1:24,000 aeromagnetic maps are interpreted as possible strike-slip faults and can be investigated in outcrop.

Outcrop observations along the northeast trend near St. Cloud show south-dipping shear surfaces with fabric that indicates the south block is upthrown and the fault has a strike-slip component. The gneisses of the northern block are in places blocky, broken and coarse-grained, but range to mylonite texture with the corresponding change of magnetite to hematite in the recrystallized regions. The presence of northwest faults is confirmed by observations in outcrops, cores, and thin sections, but

interpretation of the complex patterns awaits the completion of detailed mapping which is currently underway.

Thin sections made from red granite samples collected near faults show: faulted k-spar porphyroblasts, some with tails; mica fish; no magnetite, but abundant hematite; and chlorite and biotite partly filling ubiquitous microfractures. The reasonably euhedral zircons present, are all fractured with a very dark zircon overgrowth in the fractures indicating low-temperature shearing and metamorphism (Belden and others, 1989).

In summary, observations spanning a scale range from regional satellite images to thin sections, verify the existence of faults predicted from the accretion model. Faults trending northeast and northwest have been documented at all scales. The structural grain produced during Penokean accretion left zones of weakness for subsequent reactivation. During the Midcontinent rifting event, faults were reactivated and some filled with basalt. The recognition of ubiquitous faulting in central Minnesota should preclude any serious consideration of the area for disposal of radioactive or hazardous wastes.

#### REFERENCES

- Barovich, K.M., Patchett, P.J., Peteman, Z.E., and Sims, P.K., 1989, Nd isotopes and the origin of 1.9-1.7 Ga Penokean continental crust of the Lake Superior region: Geological Society of America Bulletin, v. 101, p. 333-338.
- Belden, J., Anderson, G., and Watkins, I., 1989, Zircons of the St. Cloud Red and Reformatory Gray granites: Institute on Lake Superior Geology Proceedings, v. 35, p. 4-5.
- Holm, D.K., and Selverstone, J., 1990, Rapid growth and strain rates inferred from synkinematic garnets, Penokean orogeny, Minnesota: Geology, v. 18, p. 166-169.
- Holst, T.B., 1984, Evidence for nappe development during the Early Proterozoic Penokean orogeny, Minnesota: Geology, v. 12, p. 135-138.
- LaBerge, G.L., and Myers, P.E., 1984, Two Early Proterozoic successions in central Wisconsin and their tectonic significance: Geological Society of America Bulletin, v. 95, p. 246-253.
- Larue, D.K., 1983, Early Proterozoic tectonics of the Lake Superior region - tectonostratigraphic terranes near the purported collision zone, in Medaris, L.G., Jr., ed., Early Proterozoic geology of the Great Lakes region: Geological Society of America Memoir 160, p. 33-47.
- Southwick, D.L., Morey, G.B., and McSwiggen, P.L., 1988, Geological map of the Penokean orogen, central and eastern Minnesota, and accompanying text: Minnesota Geological Survey Report of Investigations 37, 25 p.
- Shurr, G.W., and Watkins, I., in press, Basement blocks, tectonics, and fluid movement --- "seeping" through the sedimentary cover: Proceedings, Seventh thematic conference on remote sensing for exploration geology.

The Role of Volatiles in the Formation of the Platinum Group Element deposits in the Middle Proterozoic Duluth Complex and the Triassic Noril'sk-Talnakh Intrusions

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Over the past decade, studies of Pt-group element (PGE) deposits have focused on two contrasting facets of their probable origin (Macdonald, 1988). Much evidence documents their occurrence in mafic cumulates and relates their characteristics to the idiosyncracies of melt-crystal equilibria and physical processes of melt-crystal segregation during formation of mafic cumulates (Campbell and others, 1983). At the same time evidence has been found for syn- and post-magmatic transport and deposition from a fluid phase which could have evolved in *closed* or have been introduced in *open* magmatic systems (Ballhaus and Stumpfl, 1986; Boudreau, 1988).

The evidence described below for the role of volatiles in the origin of the occurrences of PGE's in the Middle Proterozoic Duluth Complex in the Lake Superior region and the Triassic Noril'sk-Talnakh intrusions in the Siberian platform may be related to similarities in their tectonic regimes and geologic settings (Weiblen and Morey, 1980; Urvantseva, 1971). Both are related to extensional tectonic regimes in continental crust. Both intrusions are associated with rift-related faults: the Noril'sk-Talnakh intrusions sit astride a N-NE trending fault zone and the Duluth Complex is bounded by faults which parallel the rift boundary. Drilling and geophysical data indicate that the faulting in both intrusions defines a half-graben geometry probably related to down-to-basin normal faulting in a continental rift. There is evidence that the faulting occurred prior to, during, and after intrusion.

The basement rocks of the Noril'sk-Talnakh intrusions are Devonian coal bearing shales and limestones and the country rocks for the Duluth Complex are Lower Proterozoic meta-argillites and iron formation. Both basement sequences contain abundant hydrous mineral assemblages and lesser amounts carbonaceous material and iron sulfides.

Given the nature of the host rocks and the dynamic tectonic regimes it is perhaps not surprising that both intrusions provide evidence of devolatilization of country rocks and mixing of country rocks and country rock volatiles with intrusive magmas. Evidence for these phenomena from the Cu-Ni deposits in both intrusions is shown schematically in Fig. 1. Similar textural relationships are common in the field and drill core data on Cu-Ni deposits in the Duluth Complex (Foose and Weiblen, 1986). The stable isotope studies of Ripley and his students over the years provide the greatest in-depth elucidation of the roles of country rock volatiles in the formation of the Cu-Ni deposits in the Duluth Complex (Ripley, 1986).

Evidence for volatile transport of PGE's has now been found in the Duluth Complex by Sabelin (Sabelin and others, 1989): Pt-Fe alloy and Pt-Pd sulfides are found in veins cutting olivine and chrome-spinel in a mafic cumulate in the Duluth Complex. Perhaps more striking is the discovery by Sabelin of Pd sulfide replacing chalcopyrite. Similar relationships have been alluded to in the Talnakh deposits by Genkin and Evstigneeva (1986). The discovery of a hydrous iron chloride phase (14 wt. %) by Dahlberg (pers. comm.) in a highly serpentinized section of troctolite in drill core lends credence to the concept that these replacement textures might be products of transport of PGE's as chloride complexes. There is a paucity of experimental data on volatile transport of

PGE's. However, the results of an experiment on the roasting of Cu-Ni ores in a mixture of salt and coke fragments (Iwasaki and others, 1971) indicated that segregation of the metals could be achieved with salt and coke but not with coke or other reductants alone. These results suggest that Cl is required as a transporting agent. Perhaps similar requirements must be met for PGE's to be concentrated in natural ores.

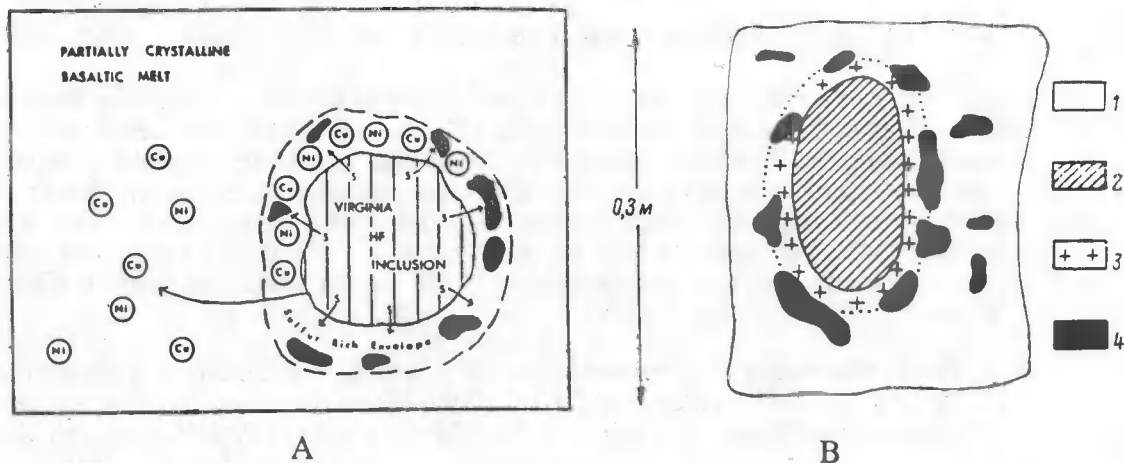


Fig. 1. Field relations of hornfels inclusions and sulfide mineralization in the Duluth Complex and the Noril'sk-Talnakh intrusions. A) Schematic representation of a pelitic hornfels inclusion in mineralized gabbro in the footwall of the Duluth Complex. Modified from Churchill (1978, p. 95). B) Inclusion in a gabbroic Noril'sk intrusion. Sulfides (4) in gabbroic pegmatoid (3) mantling a xenolith of labradorite porphyry (2) in gabbro (1). From Urvantseva (1971, p. 239). Both occurrences of sulfide can be interpreted to represent migration of sulfur from the inclusions and metals from the enclosing gabbroic magma as shown in A.

#### References

- Ballhaus, C.G. and Stumpfl, E.F., 1986, Sulfide and platinum mineralization in the Merensky Reef: Evidence from hydrous silicates and fluid inclusions. *Contrib. Mineralogy Petrology* 94: 193-204.
- Boudreau, A.E., 1988, Investigations of the Stillwater Complex. IV. The role of volatiles in the petrogenesis of the J-M Reef, Minneapolis Adit section. *Canadian Minerologist* 26: 193-208.
- Campbell, I.H., Naldrett, A.J. and Barnes, S.-J., 1983, A model for the origin of the Pt-rich sulfide horizons - the Bushveld and Stillwater Complexes. *Journal Petrology* 24: 133-165.
- Churchill, K.C., 1978, A geochemical and petrological investigation of the Cu-Ni sulfide genesis in the Duluth Complex, Minnesota. MS thesis, University of Minnesota: 101 p.
- Foose, M. and Weiblen, P.W., 1986, The physical and petrologic setting and textural and compositional characteristics of sulfides from the South Kawishiwi Intrusion, Duluth Complex, Minnesota, USA. in Friedrich, G.H., Genkin, A.D., Naldrett, A.J., Ridge, J.D., Sillitoe, R.H., and Vokes, F.M., eds., *Geology and metallogeny of copper deposits*, Soc. for Geology Applied to Mineral Deposits, Special Publication No. 4, Berlin, Springer-Verlag: 8-24.

References continued ...

Genkin, A.D. and Evstigneeva, T.I., 1986, Associations of platinum-group minerals of the Noril'sk copper-nickel sulfide ores, *Economic Geology* 81:1203-1212.

Goryainov, I.N., 1971, The genesis of the Talnakh deposit, *in* The petrology and economic geology of the Talnakh and Noril'sk differentiated intrusions, Urvantseva, N.N. (ed.)182-312.

Iwasaki, I., Takahashi, Y., and Kahata, H., 1971, Segregation process for copper and nickel ores, *in* Progress in Extractive Metallurgy, 1, Gordon and Breach, NY.

Macdonald, S.J., 1988, The platinum group element deposits: classification and genesis. *Geoscience Canada* 14: 155-166.

Sabelin, T., Weiblen, P.W., and Saini-Eidukat, B., 1989, Similarities in textures and mineral associations of platinum group minerals in the Duluth Complex, MN and the Noril'sk-Talnakh intrusions, USSR [abstr.]. *Geol. Soc. Amer. Abstr. with Prog.* 21: A262.

Urvantseva, N.N. (ed.), 1971, The petrology and economic geology of the Talnakh and Noril'sk differentiated intrusions, Leningrad,312.

Weiblen, P.W. and Morey, G.B., 1980, A summary of the stratigraphy, petrology and structure of the Duluth Complex. *American Journal Sci.* 280-A: 88-133.

## **Archean Granitoids Of Northern Marquette County, Michigan.**

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Granitoid rocks of Archean age crop out in a large portion of Marquette County, Michigan. The Archean rocks have been subdivided into the northern (granite-greenstone) and the southern (granite-gneiss) complexes. These complexes are divided by a major crustal structure: the Great Lakes tectonic zone (Sims, 1980). The granitoid rocks of the northern portion of the southern complex have been described by Hoffman (1987). The granitoid rocks of the northern complex, which have not been previously described, are the focus of this on-going study.

In the northern complex, the contact between the granitoids and the Marquette greenstone belt is gradational and foliations in the volcanics parallel those in the granitoids. The presence of abundant amphibolite xenoliths in the granitoids near the contact and compositionally similar granitoid dikes in the volcanics suggest that the granitoids intrude the volcanics. The emplacement of these belt bounding plutonic rocks is considered to be contemporaneous with recumbent folding of the volcanic rocks (Johnson and Bornhorst, in press). The granitoids range from tonalite to granite and are dominantly tonalite based on the IUGS classification (Streckeisen, 1973), and on the chemical classification scheme of Debon and Le Fort (1982). Tonalites tend to be foliated whereas granites are generally massive. Although most of these granitoids were emplaced during recumbent folding, it is possible, as discussed below that some may be younger.

Stocks and related rhyolite dikes were emplaced within the greenstone belt during a second deformational event (Johnson and Bornhorst, in press). Modally, these stocks range from diorite to granite and most are granodiorite or quartz monzodiorite. One pluton described by Puffett (1974) includes a porphyritic syenite. Age relationships between individual stocks are often equivocal because of spatial separation.

In the northern complex, both the belt bounding and intra-belt granitoids generally fall along calc-alkalic trends; however, a tonalite-trondhjemite trend is also observed in the belt bounding granitoids (Debon and Le Fort,

1982; Barker and Arth, 1976). On the basis of the major element tectonic discrimination method of Maniar and Piccoli (1989) the belt bounding granitoids on the north and northeast sides of the volcanics and the intra-belt granitoids represent an island or continental arc environment. This is consistent with the trace element discrimination method of Pearce et.al. (1984). Although these plutonic rocks were emplaced during major Archean deformation probably related to collision/suturing along the Great Lakes tectonic zone, their geochemical character is similar to an arc environment. Thus, the environment of emplacement may be transitional from arc to collision.

Granitoids which bound the southwest side of the greenstone belt in the northern complex classify as collisional granites, on the basis of major elements. This is not confirmed by the trace elements. In the southern complex, the Bell Creek Granite of Hoffman (1987) has both major and trace element composition most similar to collisional granites. Perhaps these granitoids are younger than those discussed above, and were emplaced during the mature phase of suturing along the Great Lakes tectonic zone. This hypothesis could be tested by radiometric age determinations. Although this is merely a progress report, it is clear that these Archean granitoids are a critical component to understanding the Archean in Michigan.

#### References

- Barker, F. and Arth, J.G., 1976, Generation of trondjehmitic-tonalitic liquids and Archean bimodal trondjehmitic-basalt suites: *Geology*, v.4, p. 596-616.
- Debon, F, and Le Fort, P., 1982, A chemical-mineralogical classification of common plutonic rocks and associations: *Trans. R. Soc. Edinb., Earth Sciences*, 73, p. 135-49.
- Hoffman, M.A., 1987, The geology of the southern complex: geology, geochemistry, and mineral chemistry of selected uranium-and thorium-rich granites: Ph.D. Dissertation, Michigan Technological University, Houghton, 382 p.
- Johnson, R.J. and Bornhorst, T.J., Archean geology of the northern block of the Ishpeming greenstone belt, Marquette, County, MI: U.S. Geological Survey Bulletin 1904, in press.

- Maniar, P.D. and Piccoli, P.M., 1989, Tectonic discrimination of granitoids: Geological Society of America Bulletin, v. 101, p. 635-43.
- Pearce, J.A., Harris, N.B.W, and Tindle, A.G., 1984, Trace element discrimination diagrams for the tectonic interpretation of granitic rocks: Journal of Petrology, v. 25, p. 956-83.
- Puffett, W.P., 1974, Geology of the Negaunee Quadrangle, Marquette County, Michigan: U.S. Geological Survey Professional Paper 788, 51 p.
- Sims, P.K., 1980, Boundary between Archean greenstone and gneiss terranes in northern Wisconsin and Michigan: Geological Society of America Special Paper 182, p. 113-124.
- Streckheisen, A.L., 1973, Plutonic rocks: classification and nomenclature recommended by the IUGS Subdivision on the Systematics of Igneous Rocks: Geotimes, v. 18, p. 26-30.

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