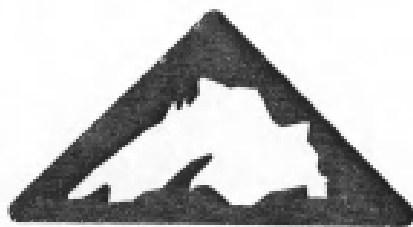


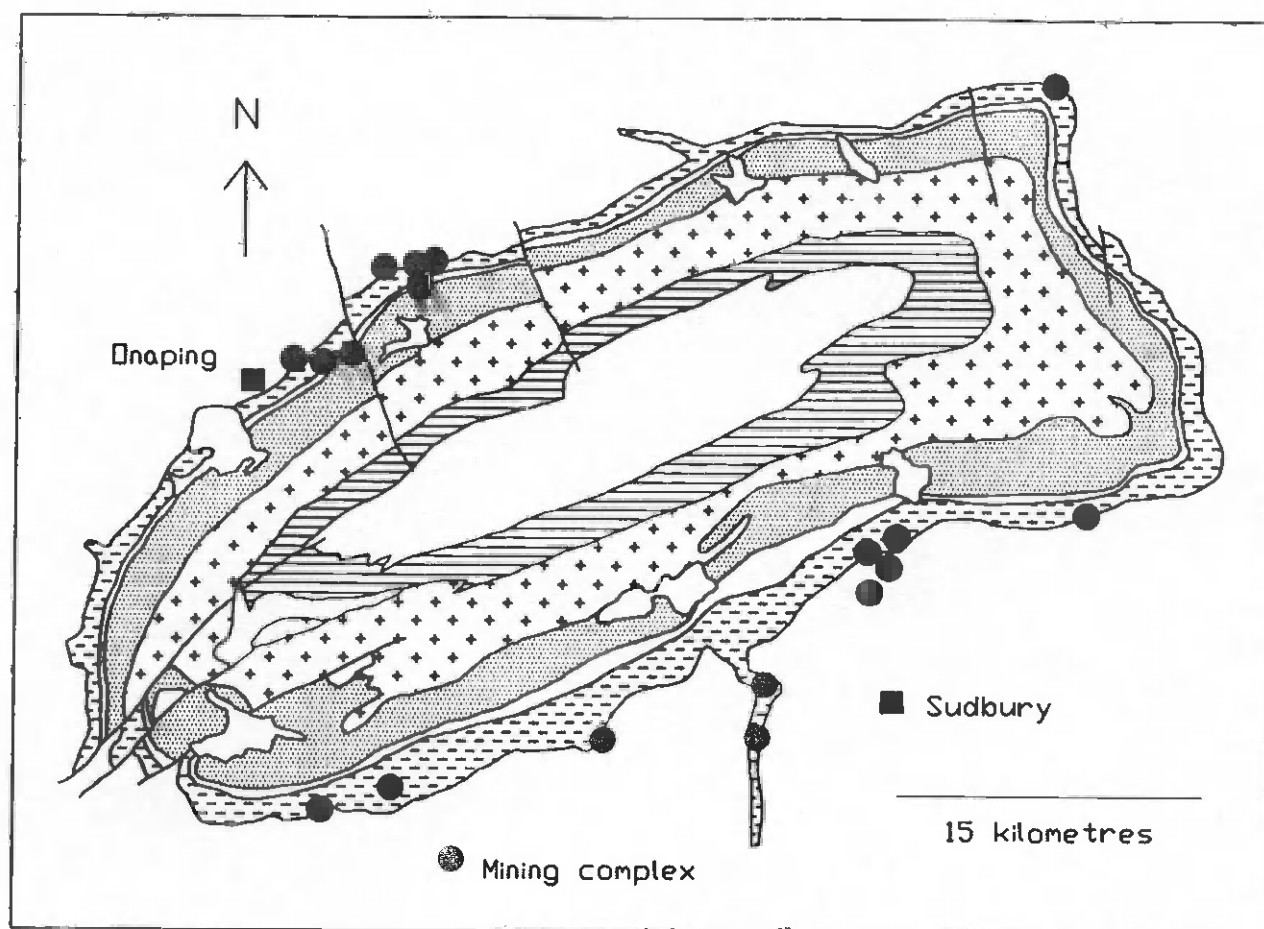
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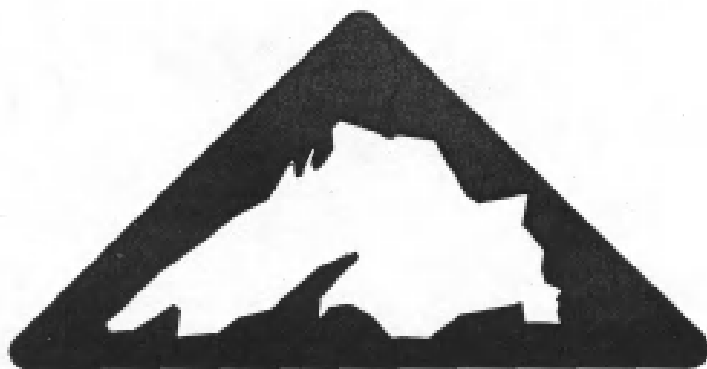
**INSTITUTE ON
LAKE SUPERIOR GEOLOGY**

**Sudbury, Ontario
May 6 - 11, 1997**



**Proceedings Volume: Program and
Abstracts**

Volume 43, Part 1



Institute on Lake Superior Geology

43rd Annual Meeting
May 6 - 11, 1997
Sudbury, Ontario, Canada

Sponsored by:
Ministry of Northern Development and Mines
Ontario Geological Survey
Resident Geologist's Office, Sudbury

Proceedings

Volume 43
Part 1 -- Program and Abstracts

Editors:
Ron Sage, Ontario Geological Survey
Wilf Meyer, Resident Geologist's Office

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Institutes on Lake Superior Geology

Institute Number	Date	Place	Chairman
1	1955	Minneapolis, Minnesota	C.E. Dutton
2	1956	Houghton, Michigan	A.K. Snelgrove
3	1957	East Lansing, Michigan	B.T. Sandefur
4	1958	Duluth, Minnesota	R.W. Marsden
5	1959	Minneapolis, Minnesota	G.M. Schwartz & C. Craddock
6	1960	Madison, Wisconsin	E.N. Cameron
7	1961	Port Arthur, Ontario	E.G. Pye
8	1962	Houghton, Michigan	A.K. Snelgrove
9	1963	Duluth, Minnesota	H. Lepp
10	1964	Ishpeming, Michigan	A.T. Broderick
11	1965	St. Paul, Minnesota	P.K. Sims & R.K. Hogberg
12	1966	Sault Ste. Marie, Michigan	R.W. White
13	1967	East Lansing, Michigan	W.J. Hinze
14	1968	Superior, Wisconsin	A.B. Dickas
15	1969	Oshkosh, Wisconsin	G.L. LaBerge
16	1970	Thunder Bay, Ontario	M.W. Bartley & E. Mercy
17	1971	Duluth, Minnesota	D.M. Davidson
18	1972	Houghton, Michigan	J. Kalliokoski
19	1973	Madison, Wisconsin	M.E. Ostrom
20	1974	Sault Ste. Marie, Ontario	P.E. Giblin
21	1975	Marquette, Michigan	J.D. Hughes
22	1976	St. Paul, Minnesota	M. Walton
23	1977	Thunder Bay, Ontario	M.M. Kehlenbeck
24	1978	Milwaukee, Wisconsin	G. Mursky
25	1979	Duluth, Minnesota	D.M. Davidson
26	1980	Eau Claire, Wisconsin	P.E. Meyers
27	1981	East Lansing, Michigan	W.C. Cambray
28	1982	International Falls, Michigan	D.L. Southwick
29	1983	Houghton, Michigan	T.J. Bornhorst
30	1984	Wausau, Wisconsin	G.L. LaBerge
31	1985	Kenora, Ontario	C.E. Blackburn
32	1986	Wisconsin Rapids, Wisconsin	J.K. Greenberg
33	1987	Wawa, Ontario	E.D. Frey & R.P. Sage
34	1988	Marquette, Michigan	J.S. Klasner
35	1989	Duluth, Minnesota	J.C. Green
36	1990	Thunder Bay, Ontario	M.M. Kehlenbeck
37	1991	Eau Claire, Wisconsin	P.E. Meyers
38	1992	Hurley, Wisconsin	A.B. Dickas
39	1993	Eveleth, Minnesota	D.L. Southwick
40	1994	Houghton, Michigan	T.J. Bornhorst
41	1995	Marathon, Ontario	M.C. Smyk
42	1996	Cable, Wisconsin	L.G. Woodruff
43	1997	Sudbury, Ontario	R.P. Sage & W. Meyer

Constitution of the Institute on Lake Superior Geology

Article I Name

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

Article II Objectives

The objectives of this organization are:

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

Article III Status

No part of the income of the organization shall 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. 290.91, 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 Chairperson, Secretary-Treasurer, and the last three past Chairpersons; 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 Chairperson and Secretary-Treasurer.

- A. The Chairperson 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/her term of office as Chairperson will terminate at the close of the annual meeting over which he/she presides or when the successor shall have been appointed. He/she 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. The term of office shall be two years or until the successor shall have been appointed.

Article VII 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-Law 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/she 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.

By-Law II Duties and Expenses

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

By-Law III Rules of Order

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

By-Law 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.

Index of Proceedings Volumes and Field Trip Guidebooks of the Institute on Lake Superior Geology 1955 - 1997

Compiled by Mark Jirsa, Secretary-Treasurer, ILSG

*Denotes abstracts volumes and guidebooks which can be ordered from the Secretary-Treasurer.
2642 University Avenue, St. Paul, MN, 55114-1057, Phone: 612-627-4539, fax: 612-627-4778, e-mail:
jirsa001@maroon.tc.umn.edu

A complete list containing such information as author, editor, chairperson, and sponsoring organization is maintained by Ms. Theresa Sanderson Spence, archivist at the J. Robert Van Pelt Library, Michigan Technological University, Houghton, MI 49931 (906-487-2505). Photocopies of back volumes can be ordered from Ms. Sanderson Spence at the prevailing copy rate. Some guidebooks were published separately by the Minnesota Geological Survey (MGS), and Wisconsin Geological and Natural History Survey (WGNHS), as indicated below; however, most are no longer available.

(Each italicized item is a separate bound document)

Volume	Year	Location
1	1955	Minneapolis, Minnesota
	<i>Program and Abstracts</i> (contains no record of field trips)	
2	1956	Houghton, Michigan
	<i>Program and Abstracts</i>	
	<i>Geological Exploration</i> (inferred to be a field guide)	
3	1957	East Lansing, Michigan
	<i>Program and Abstracts</i>	
4	1958	Duluth, Minnesota
	<i>Program and Abstracts</i>	
5	1959	Minneapolis, Minnesota
	<i>Program and Abstracts</i>	
6	1960	Madison, Wisconsin
	<i>Program and Abstracts</i>	
7	1961	Port Arthur, Ontario
	<i>Program and Abstracts</i> (misprinted label reads 6th annual meeting)	
8	1962	Houghton, Michigan
	<i>Program and Abstracts</i>	
9	1963	Duluth, Minnesota
	<i>Program and Abstracts</i>	
	<i>Field Itinerary: Stratigraphy of the Biwabik Iron Formation</i>	
10	1964	Ishpeming, Michigan
	<i>Program and Abstracts</i>	
	<i>Field Trip: Marquette iron-mining district and Republic trough</i>	
11	1965	St. Paul, Minnesota
	<i>Program and Abstracts</i>	
	<i>Field Trip Guide to the St. Cloud granite district, central Minnesota</i>	
12	1966	Sault Ste. Marie, Ontario
	<i>Program and Abstracts includes field guides to:</i>	
	1. Regional geology of the Sault Ste. Marie area	
	2. Geology and mineral deposits of the Manitouwadge Lake area, Ontario	
	3. The relationship of mineralization to the Precambrian stratigraphy, Blind River area, Ontario	
	4. Sudbury nickel irruptive tour, Ontario	
13	1967	East Lansing, Michigan

Program and Abstracts

Field Trip: Grenville Province of southeastern Ontario, Bancroft-Madoc area

- | Volume | Year | Location |
|--------|------|--|
| 14 | 1968 | Superior, Wisconsin |
| | | <i>Technical Sessions and Abstracts</i> |
| | | <i>Guide for Field Trip in the Duluth complex near Ely, Minnesota</i> |
| 15 | 1969 | Oshkosh, Wisconsin |
| | | <i>Technical Sessions and Abstracts</i> |
| | | <i>Guidebook: Central Wisconsin volcanic belt</i> |
| 16 | 1970 | Thunder Bay, Ontario |
| | | <i>Technical Sessions, Abstracts and Field Guides</i> Field Trips: |
| | | A. Proterozoic formations in the Thunder Bay area |
| | | B. Sturgeon River metavolcanic-metasedimentary formations in the Beardmore-Geraldton area |
| | | C. The Port Coldwell alkalic complex |
| | | D. Geology of the Atikokan area (title not exact) |
| 17 | 1971 | Duluth, Minnesota |
| | | <i>Technical Sessions, Abstracts and Field Guides</i> Field Trips: |
| | | A. North Shore Volcanic Group |
| | | B. Precambrian rocks of northwestern Cook County as exposed along the Gunflint Trail |
| | | C. Mesabi Range magnetite taconite |
| | | D. Geology of the Vermilion metavolcanic-metasedimentary belt, northeastern Minnesota |
| 18 | 1972 | Houghton, Michigan |
| | | <i>Part I. Technical Sessions - Agenda and Abstracts (describes trips A-D)</i> |
| | | <i>Field Trips:</i> |
| | | A. Penokean Orogeny in the central and western Gogebic region, Wisconsin and Michigan |
| | | B. Guide to Penokean deformation style and regional metamorphism at the western Marquette Range, Michigan |
| 19 | 1973 | Madison, Wisconsin |
| | | <i>Technical Program and Abstracts*</i> |
| | | <i>Field Trip: Guidebook to the geology and mineral deposits of the central part of Jackson County and part of Clark County, Wisconsin (WGNHS)</i> |
| | | <i>Field Trip: Guidebook to the Precambrian geology of northeastern and north-central Wisconsin</i> |
| | | <i>Field Trip: Guidebook to the upper Mississippi Valley base-metal district (WGNHS Information circular No. 16)</i> |
| | | <i>Bibliography of Current Research in the Lake Superior Region</i> |
| 20 | 1974 | Sault Ste. Marie, Ontario |
| | | <i>Field Trip 1: Middle Keweenaw rocks of the Batchawana-Mamainse Point area</i> |
| | | <i>Field Trip 2: unknown</i> |
| | | <i>Field Trip 3: Precambrian igneous rocks of the north shore of Lake Huron region</i> |
| | | <i>Field Trip 4: Stratigraphy and sedimentation of the Huronian Supergroup</i> |
| | | <i>Field Trip 5: The Michipicoten greenstone belt</i> |
| | | <i>Bibliography of Current Research in the Lake Superior Region (First Supplement)</i> |
| 21 | 1975 | Marquette, Michigan |
| | | <i>Proceedings</i> |
| | | Includes the following field trip guides and a supplement by Burton Boyum containing a colour map of the Marquette Mineral District: |
| | | 1. Glacial geology (trip cancelled, no guidebook) |
| | | 2. Greenstone |
| | | 3. The Jacobsville Sandstone: Evidence for a Lower-Middle Keweenawan age |
| | | 4. Marquette Iron Range |
| | | 5 and 6. The Empire Mine and Mill, Palmer, Michigan |
| 22 | 1976 | St. Paul, Minnesota |

- | Volume | Year | Location |
|--|------|--------------------------------|
| <i>Proceedings</i> | | |
| Includes abstracts and guide to Field Trip B | | |
| • Field Trip A: Minnesota River Valley field conference (no formal guidebook printed) | | |
| Field Trip B: Engineering and Pleistocene geology in the Twin Cities area | | |
| 23 | 1977 | Thunder Bay, Ontario |
| <i>Proceedings</i> | | |
| Field Trip A Geology of the Coldwell alkaline Complex | | |
| Field Trip B Proterozoic rocks of the Thunder Bay area, northwestern Ontario ("Proterozoic Trip") | | |
| Field Trip C Archean metallogeny and stratigraphy of the South Sturgeon Lake area ("Mattabi Trip") | | |
| 24 | 1978 | Milwaukee, Wisconsin |
| <i>Abstracts and Proceedings</i> | | |
| Field Trip I Southwestern Wisconsin zinc-lead district (WGNHS Field Trip Guide Book Number 1) | | |
| Field Trip II Mineral extraction and processing equipment manufacturers in the Greater Milwaukee area (no guidebook) | | |
| Field Trip III Precambrian rhyolite and granite inliers in south-central Wisconsin (WHNHS Field Trip Guide Book Number 2) | | |
| 25 | 1979 | Duluth, Minnesota |
| <i>Technical Sessions and Abstracts</i> Joint meeting with North-Central Section GSA | | |
| Field Trip Guidebooks: some were published separately as MGS Guidebook Series referenced below, the remainder are apparently unavailable. A total of eight trips were listed in GSA proceedings: | | |
| 1. Middle Precambrian volcanic and plutonic rocks of northern Wisconsin | | |
| 2. Stratigraphy, structure and mineral resources of east-central Minnesota (MGS Field Trip Guidebook series no. 9) | | |
| 3. Quaternary geology of the Duluth area | | |
| 4. Geology of the Mesabi Iron Range | | |
| 5. Geologic history and engineering geology of the western Lake Superior region | | |
| 6. Cambrian and Ordovician stratigraphy and paleontology of southeastern Minnesota | | |
| 7. Keweenaw (Upper Precambrian) North Shore Volcanic Group, Minnesota (MGS Field Trip Guidebook no. 11) | | |
| 8. Archean volcanism and sedimentation of the western Vermilion District, northeastern Minnesota (MGS Guidebook Series no. 10) | | |
| 26 | 1980 | Eau Claire, Wisconsin |
| <i>Proceedings and Abstracts</i> | | |
| Field Trip 1 Precambrian geology of the Chippewa Valley, Wisconsin. | | |
| Field Trip 2 Precambrian tectonic history of the Black River Valley | | |
| Field Trip 3 Petrology, geochemistry, and contact relations of the Wausau and Stettin syenite plutons, Central Wisconsin | | |
| Field Trip 4 Precambrian geology and tectonics of Marathon County, Wisconsin | | |
| 27 | 1981 | East Lansing, Michigan |
| <i>Abstracts and Proceedings</i> | | |
| Field Excursion Guide The Huronian rocks between Sault Ste. Marie and Thessalon, District of Algoma, Ontario | | |
| 28 | 1982 | International Falls, Minnesota |
| <i>Proceedings: Abstracts and Field Trips</i> (in one volume) | | |
| Field Trip I Mineral deposits of the Fort Frances-Mine Centre area, Ontario | | |
| Field Trip II Archean geology of the International Falls-Kabetogama area, Minnesota | | |
| 29 | 1983 | Houghton, Michigan |
| Volume I: Abstracts and Field Trip – Ropes gold mine and its geological setting | | |
| Volume II: Field guide to the geology of the Keweenaw Peninsula | | |
| 30 | 1984 | Wausau, Wisconsin |
| <i>Abstracts</i> | | |

- | Volume | Year | Location |
|---|------|--|
| | | <i>Field Trip 1</i> Guide to the geology of the Early Proterozoic rocks in northeastern Wisconsin |
| | | <i>Field Trip 2</i> Early Proterozoic tectonostratigraphic terranes of the southern Lake Superior region |
| | | <i>Field Trip 3</i> The Wausau Syenite Complex |
| 31 | 1985 | Kenora, Ontario |
| | | <i>Abstracts</i> |
| | | <i>Field Trip Guidebook</i> |
| | | 1. The Cameron Lake Deposit |
| | | 2. Geologic setting and style of gold mineralization in the Lake of the Woods area |
| | | 3. Geological relationships in the vicinity of the Wabigoon-Winnipeg River subprovincial interface in the Kenora area |
| | | 4. A volcanic facies interpretation of the Berry River Formation |
| | | 5. Granitoid related mineralization in the Dryden area |
| 32 | 1986 | Wisconsin Rapids, Wisconsin |
| | | <i>Abstracts*</i> |
| | | <i>Field Trip I</i> The Wolf River Batholith and Baraboo interval (published as Field Trip Guide Book Number 12, WGNHS) |
| | | <i>Field Trip II</i> Penokean deformation and metamorphism in central Wisconsin: volcanic rocks and gneisses (published as un-numbered Field Trip Guide Book of the WGNHS) |
| (compiler note: new reference designations were adopted to conform to ISSN standards in 1987) | | |
| 33 | 1987 | Wawa, Ontario |
| | | <i>Part 1: *Abstracts</i> |
| | | <i>Part 2: *Geology of the Wawa area and gold mineralization</i> |
| | | <i>Part 3: *Geology and stratigraphy of the Michipicoten Iron-Formation</i> |
| | | <i>Part 4: *Geology of the Hemlo Deposit</i> |
| | | <i>Part 5: *The Kapuskasing Uplift: Archean greenstones and granulites</i> |
| 34 | 1988 | Marquette, Michigan |
| | | <i>Part 1: *Abstracts</i> |
| | | <i>Part 2: Field Trip Guidebook</i> |
| | | 1. An introduction to Archean geology and precious metal mineralization of the Marquette Greenstone Belt, Michigan |
| | | 2. Marquette mineral district of Michigan, mining history and geology |
| | | 3. A structural traverse across a part of the Penokean orogen illustrating Early Proterozoic overthrusting in northern Michigan |
| 35 | 1989 | Duluth, Minnesota |
| | | <i>Part 1: Abstracts</i> |
| | | <i>Part 2: Field Trip Guidebook</i> |
| | | 1. North Shore rhyolites, Minnesota |
| | | 2. Penokean Structural Terranes in east-central Minnesota |
| | | 3. Mellen Complex, Wisconsin |
| | | 4. Archean gold occurrences and their structural settings (Virginia Horn) |
| 36 | 1990 | Thunder Bay, Ontario |
| | | <i>Part 1: Abstracts</i> |
| | | <i>Part 2: Field Trip Guidebook</i> |
| | | 1. Mafic intrusions, PGE mineralization, and granitoid rocks of Lac des Iles area |
| | | 2. Geology of the Shebandowan and Quetico Archean subprovinces |
| | | 3. Granitoid-related mineral deposits in the western Lake Superior region |
| | | 4. Base metal mineralization in the Shebandowan Greenstone Belt |
| 37 | 1991 | Eau Claire, Wisconsin |
| | | <i>Part 1: *Abstracts</i> |
| | | <i>Part 2: *Field Trip Guidebook</i> |
| | | 1. Mountain Shear Zone – a post Penokean discrete ductile deformation zone |
| | | 2. Features and significance of the Precambrian-Cambrian contact in western Wisconsin |
| | | 3. Proterozoic volcanogenic massive sulfide deposits of NW Wisconsin |

- | Volume | Year | Location |
|--------|--|--------------------|
| 38 | 1992 | Hurley, Wisconsin |
| | Part 1: *Program and Abstracts | |
| | Part 2: *Field Trip Guidebook | |
| | 1. Archean and Early Proterozoic geology of the Gogebic District | |
| | 2. Evolution of the Keweenaw sedimentary sequence | |
| | 3. Geology of the Keweenaw Supergroup at Porcupine Mountains | |
| | 4. Geology of the Great Lakes Tectonic Zone - Marquette area - a late Archean paleosuture | |
| 39 | 1993 | Eveleth, Minnesota |
| | Part 1: *Program and Abstracts | |
| | Part 2: *Field Trip Guidebook | |
| | 1. Geology and taconite mines of the Mesabi range | |
| | 2. DNR Core Library *Biwabik Iron Formation, Partridge River and South Kawishiwi intrusions, Regolith in Rotasonic cores - northern Minnesota) | |
| | 3. Geology of Archean greenstone-granite terrane: Cook-Side Lake area | |
| | 4. Duluth Complex at Duluth | |
| 40 | 1994 | Houghton, Michigan |
| | Part 1: *Program and Abstracts | |
| | Part 2: *Self-guided geological field trip to the Keweenaw Peninsula, Michigan (available from Dr. T.J. Bornhorst, 402 Emerald Street, Houghton, MI 49931-1413 (906-482-5507)) | |
| | Part 3: Volcanic geology of eastern Isle Royale, Michigan | |
| | Part 4: *Michigan kimberlites and diamond exploration techniques | |
| | Part 5: *Lessons from mining case histories: West Menominee Range, Michigan | |
| 41 | 1995 | Marathon, Ontario |
| | Part 1: *Program and Abstracts | |
| | Part 2: Field Trip Guidebooks (some may also be acquired from Ontario Geological Survey, Ministry of Northern Development and Mines, Suite B002, 435 South James Street, Thunder Bay, Ontario, Canada P7E 6E3 (807-475-1331)). | |
| | 2a. *Alkalic rocks of the Midcontinent Rift | |
| | 2b. *Geology and base metal deposits of the Manitouwadge Greenstone belt | |
| | 2c. *Geology of the Schreiber Greenstone assemblage and its gold and base metal mineralization | |
| | 2d. Geology and gold deposits of the Hemlo area | |
| | 2e. *Kimberlite, base metal, and gold exploration using overburden, Wawa area | |
| 42 | 1996 | Cable, Wisconsin |
| | Part 1: Program and Abstracts | |
| | Part 2: Volcanogenic Massive Sulfide Deposits of Northern Wisconsin: A Commemorative Volume (published in conjunction with Field Trip 3 to the Flambeau Mine) | |
| | Part 3: Field Trip Guidebook | |
| | 1. Glacial geology of western Wisconsin | |
| | 2. Geology of the Montreal River Monocline: A traverse through 25 km of crust | |
| | 4. Early to Middle Proterozoic geology of the Lake Namekagon region | |
| | 5. Lake Namekagon and Penokee Gap area, west Gogebic Range, Wisconsin | |
| 43 | 1997 | Sudbury, Ontario |
| | Part 1: Program and Abstracts | |
| | Part 2: The Huronian Supergroup between Sault Ste. Marie and Elliot Lake | |
| | Part 3: New Developments in Grenville Front Geology, Sudbury Area, Ontario | |
| | Part 4: The Sudbury Structure with Emphasis on the Whitewater Group | |
| | Part 5: Magmatic Ore Deposits of the Sudbury Igneous Complex | |
| | Part 6: Alkalic rocks of the Sudbury Region | |
| | Part 7: Regreening of Sudbury | |

Future Meeting Locations:

- | | | |
|----|------|---|
| 44 | 1998 | ? |
| 45 | 1999 | ? |

Award Guidelines Sam Goldich Medal

Preamble

The Institute on Lake Superior Geology was born in or around 1955, as documented by the fact that the 27th annual meeting was held in 1981. The Institute's continuing objectives are to deal with those aspects of geology that are related geographically to Lake Superior, to encourage the discussion of subjects and sponsoring field trips which will bring together geologists from academia, government surveys, and industry, and to maintain an informal but 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 ILSG by attending) has become aware that certain of their colleagues have made particularly noteworthy and meritorious contributions to the understanding of Lake Superior geology and mineral deposits.

The first award was made by the ILSG to Sam Goldich in 1979 for his many contributions to the geology of the region extending over some 50 years.

Award Guidelines

- 1) The medal shall be awarded annually by the ILSG Board of Directors to a geologist whose name is associated with a substantial interest in, and contribution to, the geology of the Lake Superior region.
- 2) The Board of Directors shall appoint the Nominating Committee. The initial appointment shall be of three members, one to serve for three years, one for two years, and one for one year. The member with the briefest incumbency shall be chairman. After the first year, the Board 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 ILSG membership.
- 3) By November, 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 normally will accept the nominee of the Committee, will inform the medallist immediately, and will have the 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.

Nomination Procedures

- 1) Nominations shall be taken at any time by the Goldich Medal Committee. Committee members may themselves nominate candidates. The deadline for nominations is November 1.
- 2) Nominations must be in writing and supported by appropriate documentation such as letters of recommendation, lists of publications, c.v.'s, and evidence on contributions to Lake Superior geology and to the Institute.
- 3) Nominations are not restricted to Institute attendees but are open to anyone who has worked on and contributed to Lake Superior geology.

Selection Guidelines

- 1) Nominees are to be evaluated on the basis of their contributions to Lake Superior geology (*sensu lato*) including:
 - a) importance of relevant publications
 - b) promotion of discovery and utilization of natural resources
 - c) contributions to understanding of the natural history and environment of the region
 - d) generation of new ideas and concepts
 - e) contributions to the training and education of geoscientists and the public.
- 2) Nominees are to be evaluated on their contributions to the Institute as demonstrated by attendance at Institute meetings, presentation of talks and posters, and service on Institute boards, committees, and field trips.
- 3) The relative weights given to each of the foregoing criteria must remain flexible and at the discretion of the Committee members.
- 4) There are several points to be considered by the selection committee:
 - a) an attempt should be made to maintain a balance of medal recipients from each of the three estates, industry, academia, and government.
 - b) it must be noted that industry geoscientists are at a disadvantage in that much of their work is not published.
- 5) Lake Superior has two sides, one the United States, the other Canada. This is undoubtedly one of the Institutes' great strengths and should be nurtured by equitable recognition of excellence in both countries.

Board of Directors

- 1997 **Ronald P. Sage, Co-chairman**
 Wilfried Meyer, Co-chairman
 Ontario Geological Survey, Sudbury, Ontario
- 1996 **Laurel G. Woodruff**
 U.S. Geological Survey, St. Paul, Minnesota
- 1995 **Mark C. Smyk**
 Ontario Geological Survey, Thunder Bay, Ontario
- 1994 **Theodore J. Bornhorst**
 Michigan Technological University, Houghton, Michigan
- Permanent Secretary-Treasurer**
 Mark Jirsa
 Minnesota Geological Survey
 2642 University Avenue
 St. Paul, MN 55114-1057
-

Local Committees

General Chair

Ronald P. Sage
Ontario Geological Survey, Sudbury, Ontario

Wilfried Meyer
Resident Geologist's Program, Sudbury, Ontario

Program Committee

Ronald P. Sage
Ontario Geological Survey, Sudbury, Ontario

Wilfried Meyer
Resident Geologist's Program, Sudbury, Ontario

Tracy Livingstone
Resident Geologist's Program, Sudbury, Ontario

Field Trip Committee

Ronald P. Sage
Ontario Geological Survey, Sudbury, Ontario

Wilfried Meyer
Resident Geologist's Program, Sudbury, Ontario

Tracy Livingstone
Resident Geologist's Program, Sudbury, Ontario

Secretary-Treasurer

Tracy Livingstone
Resident Geologist's Program, Sudbury, Ontario

Student Paper Committee

Jorna Kalliokoski

Professor Emeritus, Michigan Technological University

Jim Miller

Senior Geologist, Minnesota Geological Survey

Darrell Long

Department of Earth Sciences, Laurentian University

Session Chairs

Gene LaBerge

University of Wisconsin Oshkosh, Oshkosh, Wisconsin and U. S. Geological Survey

Terrence Boerboom

Minnesota Geological Survey, St. Paul, Minnesota

Mark Smyk

Ontario Geological Survey, Thunder Bay, Ontario

Mark Jirsa

Minnesota Geological Survey, St. Paul, Minnesota

Gordon Medaris, Jr.

University of Wisconsin-Madison, Madison, Wisconsin

Frank Luther

University of Wisconsin-Whitewater, Whitewater, Wisconsin

Theodore Bornhorst

Michigan Technological University, Houghton, Michigan

Phil Thurston

Ontario Geological Survey, Sudbury, Ontario

1996-97 Goldich Medal Committee

Ken Card (1997)

Consulting Geologist, Kanata, Ontario (formerly Geological Survey of Canada)

Dan England (1998)

Eveleth Fee Office, Incorporated, Eveleth, Minnesota

John Klasner (1999)

Western Illinois University, Macomb, Illinois

1997 GOLDICH MEDAL RECIPIENT

RONALD P. SAGE, ONTARIO GEOLOGICAL SURVEY

Past Goldich Medalists

1979	Samuel S. Goldich
1980	not awarded
1981	Carl E. Dutton, Jr.
1982	Ralph W. Marsden
1983	Burton Boyum
1984	Richard W. Ojakangas
1985	Paul K. Sims
1986	G. B. Morey
1987	Henry H. Halls
1988	Walter S. Whit
1989	Jorma Kalliokoski
1990	Kenneth C. Card
1991	William J. Hinze
1992	William F. Cannon
1993	Donald W. Davis
1994	Cedric Iverson
1995	Gene LaBerge
1996	David L. Southwick

1997 Banquet Speaker

Dr. Peter Lightfoot

Inco Limited
Copper Cliff, Ontario

Origin of the Sudbury Structure and its Mineral Wealth

Banquet Speaker

Dr. Peter Lightfoot
Inco Limited

Peter received his BSc degree in Geology from Worcester College, Oxford, England in 1980 and his MSc in Geology under the supervision of A.J. Naldrett from the University of Toronto in 1982. He returned to England and received his PhD in Geochemistry from the Open University, Milton Keynes, England under the supervision of C.J. Hawkesworth.

During the period of 1985 through 1987, Peter was a Post-doctoral fellow at the University of Toronto, Canada conducting research on the Nipissing diabase in the Temagami and New Liskeard area of Ontario.

In 1987 Peter joined the Ontario Geological Survey and became Supervisor, Mineral Sciences Subsection, Geoscience Laboratories until 1990. Peter played a major role in the design of the Ontario Geological Survey Geoscience Laboratories at the Willet Green Miller Centre in Sudbury.

From 1992 until 1996 Peter conducted research into mafic to ultramafic rocks for the Ontario Geological Survey. During his career, his research has included projects on the petrogenesis of the Nipissing diabase, Keweenawan flood basalt sequences, Siberian Trap lavas, Noril'sk-Tainakh intrusions and Deccan Traps. The development of sulphide accumulations in rocks of mafic and ultramafic composition has been one of his prime interests.

In 1996 Peter resigned his position at the Ontario Geological Survey to become Senior Geologist with Inco Limited in Sudbury, Ontario. Peter continues to work in mafic to ultramafic rocks and their associated sulphide mineralization. One of his current interests is the Voisey's Bay, gabbro-hosted, Cu-Ni-Co deposit in Newfoundland, Canada.

Peter resides in Sudbury, Ontario with wife Nancy, who supervises cancer research projects at Laurentian Hospital, and daughter Meagan.

CITATION

Ronald Parker Sage, 1997 S.S. Goldich Medal Recipient

Ladies and Gentlemen:

It is my pleasure tonight to introduce to you Ronald Parker Sage, the 1997 recipient of the S. S. Goldich Medal. This is the 43rd annual meeting of the Institute on Lake Superior Geology, and the 18th time the medal is being awarded.

I met Sam Goldich only once, and that happened many years ago at a conference on iron formations. From the discussions it became clear to me that he was one of the giants of Lake Superior geology. In a heated debate the moderator asked "Does anyone wish to challenge Sam Goldich on this point"? There were no takers. In last years citation, Glen Morey compared Sam Goldich to the "Drill Instructor we see on TV ads for the U.S. Marine Corps", tough, expecting his people to perform at their best, yet a wonderful man.

Before I recite to you the many accomplishments why Ron the scientist is the worthy 1997 recipient of the S. S. Goldich medal, let me tell you about Ron the person.

Ron was born in 1938 in Pontiac, Michigan, the city where he also spent his childhood and youth.

In 1974, he married Carol Ann Raebiger from Philadelphia, and they have been happily married for 23 years. While many young couples travel for their honeymoon to the sunny beaches and warm waters on some exotic tropical island, Ron and Carol chose an exotic island of another kind, they travelled to Iceland, where there are glaciers, volcanic rocks, and no tourists. Ron and Carol have three teenage children, Douglas, Victoria, and Alexandra.

Ron first graduated in 1960 with a BSc degree in geological engineering from Michigan Technological University in Houghton. While at MTU, Ron spent most of his free time collecting rocks and minerals in the copper and iron mining districts, earning him the nickname "Rocky". He was a student of Kiril Spiroff, the "Mad Russian", whom many of you will remember. Ron holds his Alma Mater in high esteem, his son Douglas is now enrolled there in a premedicine program, and daughter Victoria will follow next year to study Scientific and Technical Communications.

In the early 1960s, Ron worked for three years as Exploitation Engineer for the Shell Oil Company in west Texas. His duties included well sitting, well logging, well workovers, and other production related activities.

In 1966, Ron graduated with a Master's degree in Geology from the Colorado School of Mines. It was here that he was first exposed to alkalic rocks, his study topic and thesis being "Geology and Mineralogy of the Cripple Creek Syenite Stock, Teller County, Colorado". This led to employment with Anaconda American Brass Ltd to investigate Cu-Ni-PGE minerals in the Port Coldwell alkalic complex near Marathon, Ontario.

During the summer of 1967, Ron searched for basemetals in the Ely Greenstone Belt in Minnesota for Bear Creek Mining. It was in that year that he first met two other greats of Lake Superior geology, Ned Eisenbrey and Gene Laberge.

In 1969, Ron again worked for Anaconda American Brass Ltd, this time north of Lake Superior in the Schreiber greenstone belt, searching for gold and basemetals.

In the fall of 1969, Ron joined the Ontario Geological Survey; his professional home to this day. Ron's work for the OGS has taken him to many parts of the province, but never very far and never very long from Lake Superior. He spent the first four years on a helicopter reconnaissance in Northern Ontario, then mapped the Slate Islands in Lake Superior, and next worked on a multiyear program to study alkalic rocks north of Port Coldwell along the northern extension of the Trans Superior Tectonic Zone and along the Kapuskasing Structural Zone. In 1978, Ron was assigned to the Michipicoten greenstone belt. Here he spent 10 years

mapping Archean supracrustal rocks over approximately 540 square miles, with emphasis on the gold and base metal potential. In 1993, Ron was assigned to a province wide program of kimberlite occurrences to stimulate diamond exploration. Some of this work was again in the Michipicoten area, where diamond indicator minerals are common.

Despite his busy professional schedule, Ron was able to complete his PhD degree in 1986 for a thesis submitted to Carleton University in Ottawa. The topic: "Alkalic Rock Complexes and Carbonatites of Northern Ontario, and their Economic Potential".

Student Travel Award

The 1986 Board of Directors established the I.L.S.G. Student Travel Award to support student participation at the annual meeting of the Institute. 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 annual meeting 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 favoured 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.

42nd Annual Institute on Lake Superior Geology Cable, Wisconsin

The 42nd Annual Institute on Lake Superior Geology was held May 15 - 19, 1996, at the Telemark Lodge in Cable, Wisconsin. The meeting was organized by the U. S. Geological Survey (Chair, Laurel Woodruff, Field Trip Coordinators, William Cannon and Suzanne Nicholson), and the University of Wisconsin - Oshkosh (Field Trip Coordinator, Gene LaBerge, Secretary/Treasurer, Sally LaBerge).

The Proceedings of the 42nd ILSG were published in 3 parts:

Part I: Program and Abstracts (edited by Laurel Woodruff and Suzanne Nicholson)

Part II: Volcanogenic Massive Sulfide Deposits of Northern Wisconsin: A Commemorative Volume (edited by Gene L. LaBerge)

Part III: Field Trip Guidebook (edited by Suzanne Nicholson and Laurel Woodruff)

Part 1: Glacial Geology of Western Wisconsin (Mark D. Johnson)

Part 2: Overview of the Bedrock Geology of the Cable-Hurley Area, Wisconsin (William F. Cannon and Suzanne W. Nicholson)

Part 3: Geology of the Montreal River Monocline - A Traverse through 25 km of the Crust (William F. Cannon)

Part 4: Early to Middle Proterozoic Geology of the Lake Namekagon Region (William F. Cannon, Laurel G. Woodruff and Suzanne W. Nicholson)

Part 5: Lake Namekagon and Penoque Gap Areas, West Gogebic Range, Wisconsin (John S. Klasner and Gene L. LaBerge)

The commemorative massive sulfide volume, originally conceived by Edward May, consulting geologist at the Flambeau Mine, and dedicated to Edward H. Eisenbrey and John S. Phillips, early pioneers in the exploration and study of massive sulfide deposits in Wisconsin, was published in conjunction with a post-meeting field trip to the Flambeau gold-copper mine in Ladysmith, Wisconsin. The volume contains nine chapters:

History of exploration for volcanogenic sulfides (Russell C. Babcock)

General characteristics and geologic setting of the Wisconsin magmatic terrains (Gene L. LaBerge)

A geologic framework for Early Proterozoic volcanogenic massive sulfide deposits in Wisconsin (Theodore A. DeMatties)

An overview of the Flambeau supergene enriched massive sulfide deposit: Geology and mineralogy, Rusk County, Wisconsin (Edward R. May and Stephen R. Dinkowitz)

Case study of environmental requirements for the permitting, operation, and reclamation of a metallic mine in Wisconsin - Flambeau Mine (Jana E. Murphy and Richard T. Dachel)

Eisenbrey: A structurally complex Proterozoic copper-zinc massive sulfide deposit, Rusk County, Wisconsin (Edward R. May)

Geological Summary - Crandon deposit (A. J. Erickson and R. Cote)

The Bend deposit: An Early Proterozoic copper-gold VMS deposit (Theodore A. DeMatties and William F. Rowell)

Geology of the Lynne base-metal deposit, north-central Wisconsin, U.S.A. (Glen A. Adams)

Gene LaBerge undertook the formidable task of organizing the volume. Most of the printing costs for the volume were generously donated by a number of individuals and corporations. Proceeds from the sale of the volume will be used to promote student participation in future ILSG meetings.

A total of 148 people registered for the meeting in Cable. Field trips associated with the meeting were robust, with 177 paid participants, including 11 for the glacial geology of northern Wisconsin, 43 on the Archean-Middle Proterozoic transect trip, 18 looking at the Early Proterozoic in the Lake Namekagon region, and 17 on the trip to the Penoque Gap. The trip to the Flambeau Mine was one of the last official trips to the mine prior to the start of planned shut down phase, and had 88 participants. Many logistical details for the trip were generously supported by Kennecott Copper and the Flambeau Mining Company.

The annual banquet was attended by 111 diners. The Goldich Medal was awarded to David Southwick of the Minnesota Geological Survey in recognition for his outstanding contributions to geology in the Lake Superior region. Glen Morey, also from the Minnesota Geological Survey, presented the award. To correct an oversight during the annual meeting of the ILSG Board of Directors, the term of the Secretary/Treasurer (Mark Jirsa) was approved by a belated, but unanimous act. The banquet address was given by Dr. Stephen E. Kesler of the University of Michigan, presenting a well-received lecture titled, *Sustainable Mineral Development -- Fact or Fiction*.

Student Paper Awards were given to Kimberly Darrah (Kent State University) for her talk on *Petrographic and thermobarometric analysis of the metamorphosed Little Falls Formation, Central Minnesota, with implications for Early Proterozoic tectonism*; Susan Wilson (Western Illinois University) for her talk, *A structural and kinematic analysis of the McCaslin Formation near McCaslin Mountain, Wisconsin*, and Zachary Naiman (Macalester College) for his poster, *Metamorphism of Chengwatana Volcanic Group near Taylors Falls and from Osseo core*. Five student travel awards totalling \$400 were presented to Zachary Naiman, Kim Neilson, Andrey Bekker, Susan Wilson, and Kimberly Darrah.

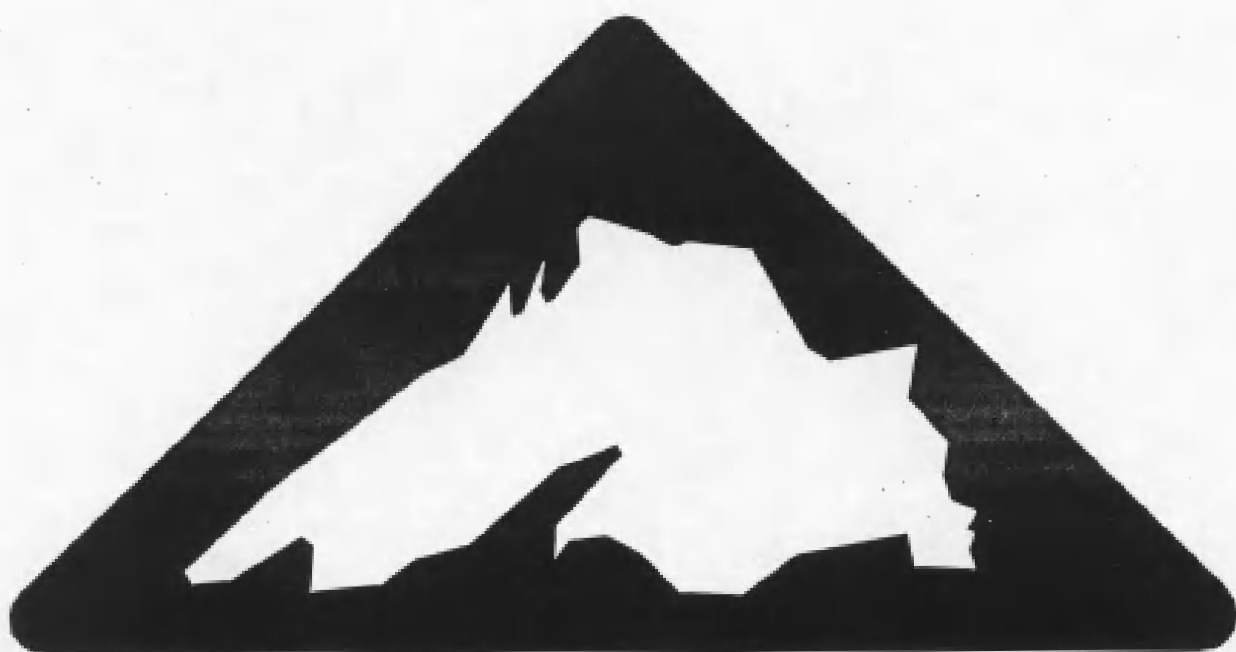
The Board of Directors of the Institute on Lake Superior Geology met in Cable on May 16, 1996. Members of the Board in attendance were: Laurel Woodruff (Chair), Mark Jirsa (Secretary/Treasurer), Ted Bomhorst, David Southwick, and Mark Smyk. Invited guests included: Ken Card, Ron Sage, Wilf Meyer, Charles Blackburn, Gene LaBerge and Sally LaBerge. Actions taken were:

1. Accepted the Report of Chairman, 41st ILSG meeting (Mark Smyk), which included the minutes of the last Board meeting.
2. Approved an offer by the Ontario Geological Survey to host the 43rd Annual Institute on Lake Superior Geology in Sudbury, Ontario. Ron Sage and Wilf Meyer will act as co-chairs for the meeting.
3. Approved Kenora, Ontario, and the Ontario Geological Survey as host for the 44th ILSG in 1998, with Charles Blackburn as Chair.
4. Accepted ILSG Financial Report from the Secretary/Treasurer Mark Jirsa.
5. Approved David Southwick as recipient of 1996 Goldich Medal.
6. Approved John Klasner as new Goldich Medal Committee member (replacing Penny Morton).
7. Discussed the future of the ILSG Newsletter and the establishment of a home page for the ILSG. Results from the members poll in the first newsletter were presented. The Board approved the continuation of the newsletter at the rate of one/annum with Ted Bomhorst carrying the initiative for both activities.
8. Discussed the distribution and continued sale of back issues of ILSG Field Trip Guidebooks, which are being handled by Mark Jirsa as Secretary/Treasurer.
9. Discussed the recent publication of Proceedings Volume 42, Part 2 – the commemorative volume on Wisconsin massive sulfides. The Board agreed to send a letter of thanks to all the contributors who donated money for the publication of the volume. Proceeds from the sale will be used for the encouragement of student participation in the ILSG, and will be kept separate from the general working fund. With the Board's approval Ted Bomhorst will promote the advertising and sale of the volume.
10. The Board approved changes to the constitution of the ILSG voted on by the participant members of the ILSG during the morning Technical Session on May 16, 1996. These changes included wording changes to make the constitution gender neutral, and an extension for the term for the Secretary/Treasurer, which was actually carried out at the annual banquet. To establish a list of members for the ILSG, the Board agreed to create a comprehensive mailing list which includes both permanent members (those participants with long-standing interest in Lake Superior geology) and a list of members who have attended ILSG meetings in the past. The Board assigned Laurel Woodruff to complete this membership mailing list, which will then be passed from Chair to Chair for successive meetings. Membership dues will not be assessed at this time.
11. In a discussion of requirements and suggestions to ILSG Chairs, it was determined that the Chair needs the freedom to act independently within reasonable intuitive guidelines that follow general historical precedents.
12. The Board discussed a presentation by Ken Card on the standardization of the selection policy for the Goldich Medal award. The matter was tabled for future review.
13. The Board agreed that the Student Paper Committee needs the freedom to act independently within reasonable intuitive guidelines and need not be constrained by historical precedents.

Budgeting for the 42nd ILSG was done to keep costs within reasonable limits, and not lose money. This was successful, as the meeting made an approximate profit in excess of \$6000. However, as much as the Chair would like to claim credit for this, a substantial portion of this sum was a result of support from the Flambeau Mining Company for the Flambeau Mine field trip. In addition, with many of the publishing costs for the Proceedings Volume 2 underwritten by the numerous contributions from individuals and companies all future sales will directly profit the Institute's student participation fund.

I enjoyed my tenure as Chair of the Institute on Lake Superior Geology, and the opportunity to interact with people associated with the organization. There are a number of people involved with the meeting who were essential to its overall success and the Chair's general well-being. I thank Gene and Sally LaBerge, who coaxed and guided me through the experience and without whom it would have been nearly impossible, and Suzanne Nicholson who was more than willing to do everything I asked her to do, and it was alot. Bill Cannon originally conceived of the USGS sponsoring an ILSG and then generously deferred the duties of Chair to me, rather than taking on the glory for himself, former Chairs Ted Bornhorst and Mark Smyk willingly gave advice, and Secretary/Treasurer Mark Jirsa covered all the money questions for me.

Laurel Woodruff
Chairman, 42nd ILSG
Cable, Wisconsin



PROGRAM

Calendar of Events and Program

Tuesday May 6, 1997

8:00 a.m. - 7:00 p.m. Field Trip 1

Field Trip 1 - *The Huronian Supergroup between Sault Ste. Marie and Elliot Lake*
(day 1)

Leaders: Ken Card (Geological Survey of Canada, retired)
Gerry Bennett (Resident Geologist, Sault Ste. Marie, Ontario Geological Survey)

Wednesday, May 7, 1997

8:00 a.m. - 6:30 p.m. Field trips 1, 2, 3, 4

Field Trip 1 - *The Huronian Supergroup* (day 2)

Leaders: as above

Field Trip 2 - *New Developments in Grenville Front Geology, Sudbury Area, Ontario*

Leader: Tony Davidson (Geological Survey of Canada)

Field Trip 3 - *The Sudbury Structure with emphasis on the Whitewater Group*

Leader: Stu Gibbons (Falconbridge Limited)

Field Trip 4 - *Magmatic Ore Deposits of the Sudbury Igneous Complex*

Leader: Steve Prevec (Laurentian University)

Mike Cosec (Resident Geologist's Program, Ontario Geological Survey)

7:30 p.m. - 9:30 p.m. Registration, Poster Set-up

Alphonse Raymond Building, Laurentian University Campus

7:30 p.m. - 10:00 p.m. Icebreaker, Cash Bar

Alphonse Raymond Building, Laurentian University Campus

Thursday, May 8, 1997

NOTE: Technical Sessions are in the auditorium, Alphonse Raymond Building, Laurentian University Campus

8:00 a.m. - 4:30 p.m. Registration continues

Technical Session 1

Session Chairs: Gene LaBerge and Terrence Boerboom

- 8:30 a.m. Andy Fyon
Senior Manager, Precambrian Geoscience Section, Ontario Geological Survey
Opening Remarks - 43rd Annual Institute on Lake Superior Geology
- 8:40 Don Rousell
The Tectonic, Magmatic and Mineralization History of the Sudbury Structure
- 9:40 T. F. Morris
Results of modern alluvium sampling for kimberlite indicator minerals, Wawa-Kinniwabi Lake Region and the implication for kimberlite exploration, Northeastern Ontario
- 10:00 Coffee Break and Poster Session
Sponsored by Falconbridge Limited Exploration
- 10:20 Shawn M. Carlson and Glen W. Adams
The diamondiferous six-pak ultramafic lamprophyric diatreme, Kenosha, WI
- 10:40 Dean M. Peterson
GIS applications for Archean gold exploration: using Canadian mining camp GIS queries to target gold exploration in Minnesota
- 11:00 Keri Anderson and Nigel Wattrus
A seismic stratigraphic study of Western Lake Superior
- 11:20 C. M. Mancuso, D. K. Holm, K. A. Foland and F. A. Hubacher
Initial results of Ar/Ar mineral dating from the Peavy node area of northern Michigan and Dunbar dome area of northeastern Wisconsin
- 11:40 D. K. Holm and D. H. Henderson
Space-time patterns of Early Proterozoic post-Penokean (1800-1600 Ma) metamorphism and cooling in the southern Lake Superior region
- 12:00 p.m. Lunch Break

Technical Session 2

Session Chairs: Mark Smyk and Mark Jirsa

- 2:00 Gene L. LaBerge
The Early Proterozoic break-up of the Superior Craton: Implications of drill core and geophysical data south of the Gogebic range, northern Wisconsin
- 2:20 T. Arcuri and E. M. Ripley
Interaction between a Virginia Formation xenolith and mafic magma at the Babbitt Cu, Ni deposit Duluth complex, MN
- 2:40 Edward M. Ripley, David D. Lambert and Louise R. Frick
Re-Os, Sm-Nd and Pb isotopic constraints on mantle and crustal contributions to magmatic sulphide mineralization in the Duluth complex
- 3:00 Coffee Break and Poster Session
Sponsored by Ministry of Northern Development & Mines
- 3:20 John Siriunas and John Wiebe
Overview of the Gregor Goldfields Corp. Marathon (Wire Lake) Gold Property in the Hemlo Area of central Ontario, Canada
- 3:40 Tom Muir
The Hemlo Gold Deposit: It may be gold but its not black and white
- 4:00 Steve Jackson
Patterns of structure and metamorphism in the Hemlo greenstone belt
- 6:30 - 7:30 Mixer - cash bar
Cavern, Science North
- 7:30 - 9:30 Annual Banquet and Awards Presentation
Announcement of the 44th Annual Meeting location
1997 Goldich Award presentation to Ronald P. Sage
Banquet speaker: Dr. Peter Lightfoot, Inco Limited, Copper Cliff,
Ontario: *Origin of the Sudbury Structure and its mineral wealth*

Friday, May 9, 1997

Technical Session 3

Session Chairs: Gordon Medaris, Jr. and Frank Luther

8:30 a.m. Registration continues

- 9:00 George Hudak and Ron Morton
The evolution of the hydrothermal systems associated with the Sturgeon Lake Caldera complex, northwestern Ontario
- 9:20 Jon Devaney
Stratigraphy, tectonics and mineralization of the Sioux Lookout orogenic belt, Western Wabigoon Subprovince
- 9:40 Gerry Bennett
The Huronian - from the bottom up
- 10:25 Coffee Break and Poster Session
Sponsored by Laurentian University
- 10:45 Steve Jackson
Structural and metamorphic constraints on the tectonic history of the Southern Province in the Sault Ste. Marie - Espanola area
- 11:05 Robert G. Tipping and Douglas Allen
Hydrogeology of saline- and boron-bearing ground waters in the North Shore volcanic group - Minnesota
- 11:25 Douglas Allen, W. E. Seyfried, Jr., and R. G. Tipping
Boron, bromide and chloride in groundwaters and rocks of the north shore of Lake Superior - evidence for a seawater incursion into the mid-continent rift
- 11:45 Richard W. Ojakangas
Correlative sequences within the Marquette Range Supergroup (Michigan) and the Huronian Supergroup (Ontario): Glaciogenics, paleosols and orthoquartzites
- 12:05 Hank Woodard
The McKenzie Lake Antiform and the Kawa Bay Synform, Quetico Provincial Park, Ontario
- 12:30 p.m. Lunch break (remove posters)

Technical Session 4

Session Chair: Ted Bornhorst and Phil Thurston

- 2:00 E. Zaleski, O. van Breemen and V. L. Peterson
Age constraints on plutonism, metamorphism and deformation across the Wawa-Quetico Subprovince boundary near the Manitouwadge Greenstone belt, northwestern Ontario

- 2:20 L. G. Medaris, Jr., L. P. Baumgartner, R. H. Dott and K. McSweeney
The Sub-Baraboo Paleosol, Wisconsin: geochemical evidence for
Proterozoic weathering and metasomatism
- 2:40 Keith Winterhalder
The greening of Sudbury
- 3:05 Coffee Break
- 3:25 Gerard Doiron, Masood Siddiqui and Mark Smyk
Preliminary investigations of the Pick Lake deposit, Winston Lake Mine,
Ontario: A remobilized massive sulphide orebody
- 3:45 Theodore Bornhorst and Laurel Woodruff
Native copper precipitation by fluid-mixing, Keweenaw Peninsula, Michigan
- 4:05 Frank R. Luther
The petrology of greenschist: a Proterozoic porphyritic diabase dike; Pifher
and Irwin townships, Lake Nipigon District, Ontario
- 4:25 Presentation of Student Paper Awards
- 4:30 Closing Remarks

Saturday, May 10, 1997

8:00 a.m. - 7:00 p.m. Field trips 3, 4, 5, 6

Field Trip 3 - *The Sudbury Structure with emphasis on the Whitewater Group*
Leader: Stu Gibbons (Falconbridge Limited)

Field Trip 4 - *Magmatic Ore Deposits of the Sudbury Igneous Complex*
Leader: Steve Prevec (Laurentian University)
Mike Cosec (Resident Geologist's Program, Ontario Geological Survey)

Field Trip 5 - *Alkaline rocks of the Sudbury Region (day 1)*
Leader: Ron Sage (Ontario Geological Survey)

Field Trip 6 - *Regreening of Sudbury*
Leaders: Keith Winterhalder (Laurentian University)
John Gunn (Laurentian University)

Sunday, May 11, 1997

8:00 a.m. - 7:00 p.m. Field Trip 5

Field Trip 5 - *Alkalic rocks of the Sudbury Region (day 2)*

Leader: Ron Sage (Ontario Geological Survey)

Poster Session

Wednesday, May 7, 1997 (set-up begins at 7:30 p.m.) -

Friday, May 9, 1997 (tear-down at 12:00 p.m.)

Dave Dahl

Minnesota Department of Natural Resources

Gravity Aspect as a Tool for Recognizing Crustal Fabric and Structure at
Minnesota

Jon Devaney

Ontario Geological Survey

Stratigraphy, tectonics and mineralization of the Sioux Lookout orogenic belt,
Western Wabigoon Subprovince

Mike Easton

Ontario Geological Survey

R. S. James

Department of Geology, Laurentian University

Revisiting the disappearance of the Huronian in the Sudbury-Crerar area:
insight from the geochemistry of amphibolites and paragneisses

D. K. Holm

Department of Geology, Kent State University

D. R. Lux

Department of Geological Sciences, University of Maine

Results of Ar/Ar dating of dikes in central Minnesota and the Minnesota River
Valley

Tom Lawler and Darold Riihiluoma

Department of Natural Resources, Division of Minerals, State of Minnesota

Mineral potential study of a greenstone belt using boulder tracing, Ely-Bigfork
area, Minnesota

T. F. Morris

Ontario Geological Survey

Results of modern alluvium sampling for kimberlite indicator minerals,
Wawa-Kinniwabi Lake Region and the implication for kimberlite exploration,
Northeastern Ontario

Tom Muir

Ontario Geological Survey

The Hemlo gold deposit area: a surface perspective

Zachary Naiman and Karl R. Wirth

Geology Department, Macalester College

Petrogenesis of Chegwatana volcanics, Minnesota and Wisconsin

John M. Siriunas and Neil Willoughby

NR&J Resource Associates Limited

Copper and precious-metal mineralization in Eastern Sault Ste. Marie Mining
Division with focus on the Jentina Property, Albanel and Nicholas townships,
District of Algoma

T.E. Wahl, J.D. Miller Jr., M.A. Jirsa, T.J. Boerboom, V.W. Chandler, A.C. Runkel

Minnesota Geological Survey

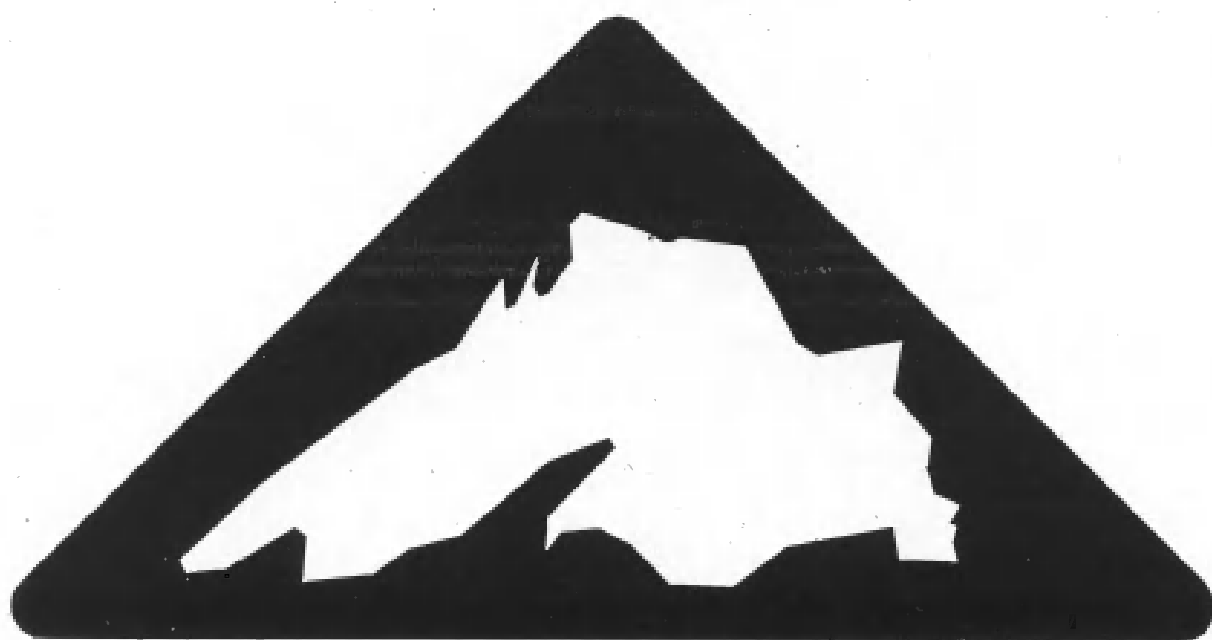
D. Dahl

Minnesota Department of Natural Resources, Division of Minerals

M.J. Severson

Natural Resources Research Institute, University of Minnesota

Geologic mapping system (GeMS): A digital approach to bedrock geologic
mapping



ABSTRACTS

Boron, bromide and chloride in groundwaters and rocks of the North Shore of Lake Superior, evidence for a seawater incursion into the Mid-Continent Rift

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Two geochemically distinctive groundwater types have been recognized in the North Shore Volcanic Group (NSVG) rocks of the North Shore of Lake Superior, Northeast Minnesota. The chemistry of these groundwaters may contain evidence of a seawater incursion into the Mid-Continent Rift.

The most widespread groundwater type is characterized by high pH and boron concentrations, which reach values of 10.26 and 5.4 ppm, respectively. The Minnesota Department of Health, Health Risk Limit, for boron in drinking water is 0.6 ppm (STS Consultants Report, 1995), so the genesis and distribution of these waters is of some concern, as well as being of interest geochemically. The second groundwater type is a Ca-Cl brine, which has a dissolved chloride concentration nearly twice that of seawater, and has a conspicuously high Br/Cl ratio (0.0089).

Mineral-fluid equilibria calculations reveal that the high pH groundwaters plot within the quartz-kaolinite-laumontite-calcite stability field (fig. 1). This assemblage of minerals is ubiquitous in the North Shore basalts (Schmidt, 1993). As evidenced by figure 1, the laumontite-bearing assemblage fixes $p\text{CO}_2$ at relatively low values ($\log p\text{CO}_2 = -5.2$ at 25°C), which helps to account for the relatively high pH groundwaters in the NSVG rocks.

Preliminary boron isotope data for the North Shore groundwaters reveal δB^{11} values ranging from +21 (Ca-Cl brine) to +45.5. Typical δB^{11} values for crystalline rock and non-marine brines and sedimentary sources are well below +20 (Barth, 1993). Rocks formed in marine environments and brines derived from seawater ($\delta\text{B}^{11} = +39.5$), however, can have δB^{11} greater than +50 (Barth, 1993). Thus, interaction of NSVG rocks with seawater derived fluids during late stage and post rifting events could have resulted in uptake of seawater derived boron during basalt weathering and hydrothermal alteration. Indeed, NSVG rocks are variably enriched in boron and have concentrations as high as 33 ppm (interflow sedimentary unit). Subsequent interaction of the boron-rich alteration minerals with high pH groundwater would enhance mineral dissolution, and help to account for the high boron-bearing groundwaters.

A positive linear correlation exists between dissolved bromide and chloride concentrations in the groundwaters (fig. 2). A positive correlation between mutually conservative elements such as bromide and chloride suggests a common source for these elements. This can be explained by the mixing and accompanying dilution of an end-member brine. There is a negative correlation between boron and chloride, however, which is consistent with a model involving boron uptake from seawater, decoupling the controls on dissolved boron from those of dissolved chloride and bromide.

Boron concentrations and isotopic composition of NSVG groundwaters, as well as the bromide and chloride data, suggest a model involving seawater evaporation and subsequent rock alteration. It is not unreasonable that such a seawater incursion resulted in the characteristic marine boron isotopic imprint on the rocks and residual brines of the rift. Interaction of these altered rocks and brines with modern groundwater systems result in the distinctive nature of the North Shore groundwaters.

Figure 1

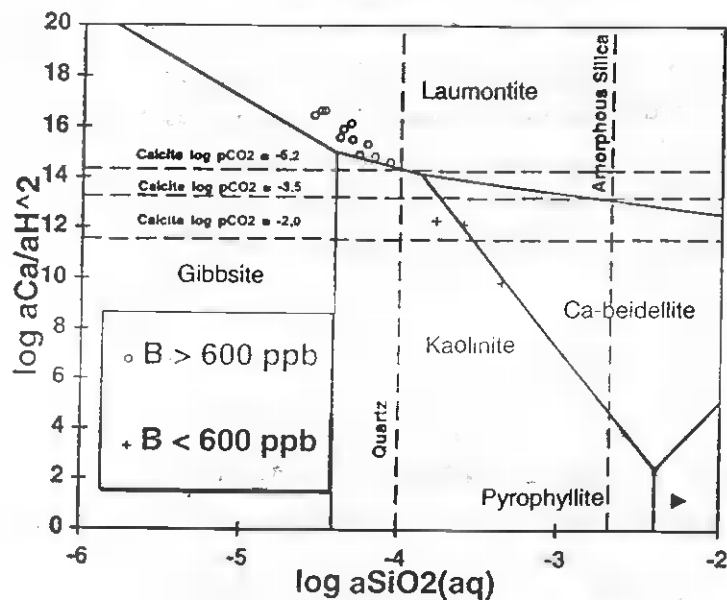
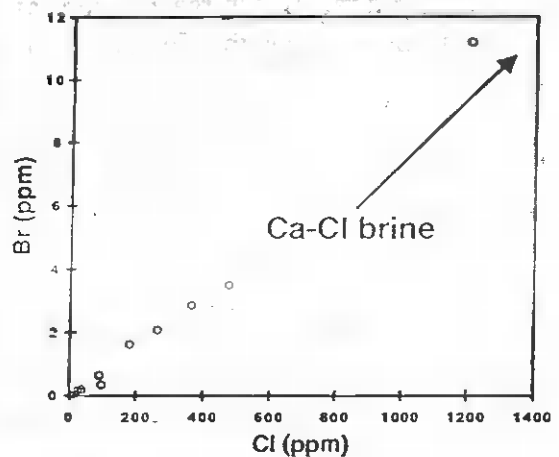


Figure 2



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A SEISMIC STRATIGRAPHIC STUDY OF WESTERN LAKE SUPERIOR

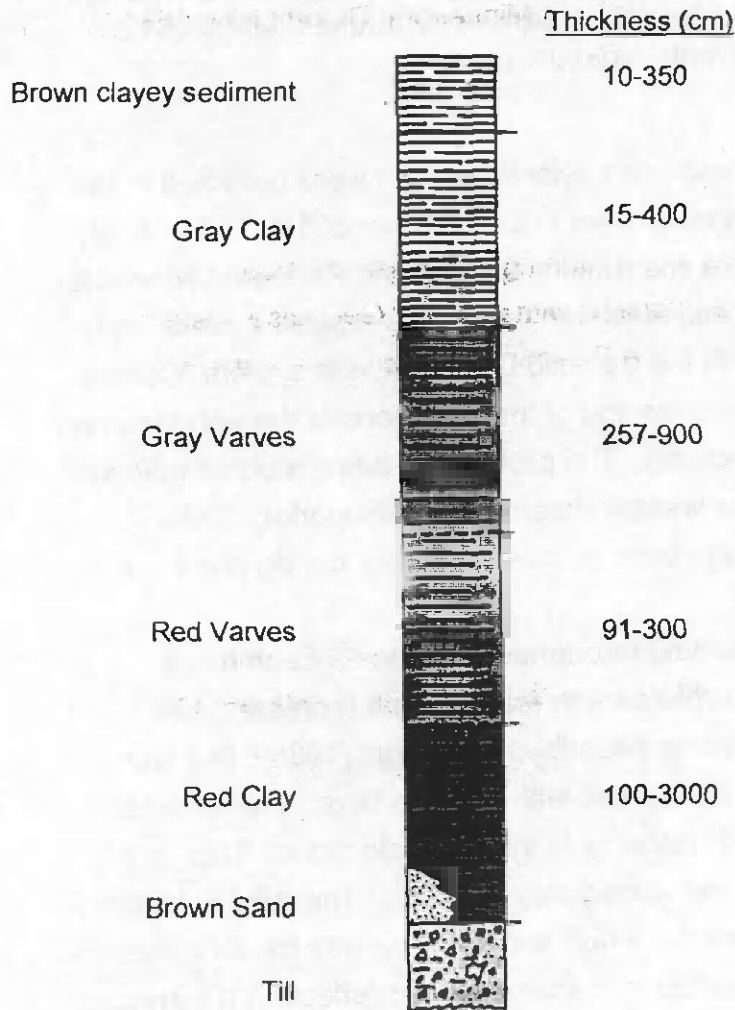
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Approximately 1000 km of high resolution seismic profiles were collected in the western third of Lake Superior during three cruises in the summer of 1996. The study area extends from Duluth, Minnesota to a line running from Grand Portage, Minnesota to Houghton, Michigan. The data were acquired with an ORE Geopulse system and digitally recorded for later processing with the Seismic UNIX software system (Cohen and Stockwell, 1996). Post acquisition processing of the data permits the enhancement of subtle features not visible in paper sections. The profiles are being studied to identify and describe seismic reflectors within the western basin of Lake Superior. The interpreted profiles are then correlated with several cores collected during previous cruises in this part of the lake.

Four reflectors are commonly observed throughout the basin. Each has a distinct acoustic signature and can be correlated with features in a representative section (Figure 1) of Lake Superior sediments described by Scholz (1985). The first reflector is strong and continuous and is associated with the lake floor. The second reflector has a strong, wavy character with discernible internal reflections. This discontinuous reflector is correlated with the varved clay horizons. The third reflector has a strong, discontinuous acoustic character which is correlative with the till horizon described by Scholz (1985). The fourth reflector is a strong, hard reflector. It's irregular surface and the presence of scattered channels throughout associate it with bedrock.

A map of sediment cover for Western Lake Superior generated from this data shows regions of the basin where sediment focusing is occurring. Acoustic reflectivity (in conjunction with data from coring) is used to produce a distribution map of sediment type in the basin. This information will further our understanding of circulation dynamics within the western basin and will help to improve sampling strategies for future investigations of sediment binding contaminants.

**Idealized Stratigraphic Section of
Lake Superior Sediments**



(After Scholz, 1985)

Figure 1

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INTERACTION BETWEEN A VIRGINIA FORMATION XENOLITH AND MAFIC MAGMA AT THE BABBITT CU-NI DEPOSIT, DULUTH COMPLEX, MN.

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Previous work on the Duluth Complex, MN, has shown the importance of the interaction between Virginia Formation xenoliths and tholeiitic magmas in the formation of sulfide mineralization. In this study the effects of a single xenolith on the surrounding igneous rocks were examined from drill core in order to assess: 1) if *in situ* introduction of sedimentary sulfur was an important factor in the formation of the massive sulfide layer at the top of the xenolith, 2) if a flow path of a partial melt derived from the xenolith can be determined from major element gradients, 3) if sulfur and oxygen isotopic gradients were preserved at the xenolith contacts, and if so to model their origins using mass balance and diffusion calculations.

Sulfur isotopic values of disseminated and lenticular pyrrhotite in the xenolith vary from 12.4 to 17.4‰ with the variation thought to reflect primary layer to layer differences in the protolith (Fig. 1). The massive sulfide at the upper contact of the xenolith is characterized by $\delta^{34}\text{S}$ values of 12.0 to 12.4‰. In the igneous rock above the massive sulfide, $\delta^{34}\text{S}$ values range from 10.7 to 11.5‰. These values are strongly suggestive of a sedimentary source for the sulfur in the sulfide minerals; taken together with the pyrrhotite-rich nature of the sulfide the $\delta^{34}\text{S}$ values are also consistent with an *in situ* origin of the massive mineralization at the xenolith border. Andrews and Ripley (1989) detected a negative correlation between whole rock S content and Fe/Mg ratios of orthopyroxene and biotite in Virginia Formation footwall rocks. This relationship was attributed to sulfur fixation in the country rocks and the sulfurization of Fe-bearing silicates. The opposite relationship was observed in the xenolith from core B1-127, suggesting that sulfurization of Fe-bearing silicates was not a major process and that Fe/Mg ratios of minerals in the xenolith reflect differences in bulk composition between original sedimentary layers. The $\delta^{34}\text{S}$ values of the igneous rocks below the xenolith are very different from those in the igneous rocks above the xenolith, and range from -2.8 to 5.2‰.

Oxygen isotopic values also show very different trends above and below the xenolith (Fig. 1). $\delta^{18}\text{O}$ values of the xenolith vary from 9.8 to 11.7‰, with the lowest value near the upper contact. $\delta^{18}\text{O}$ values of the overlying igneous material gradually decrease to normal values of 6.2‰ over a 30 foot interval. A much sharper $\delta^{18}\text{O}$ gradient is found at the lower contact, with $\delta^{18}\text{O}$ values of 5.8 to 6.3‰ found in the igneous rocks within a distance of less than 1.5 feet.

Major element analysis of the xenolith indicate that it has undergone extensive partial melting, with the loss of a Si-rich, K- and Na-bearing component. Unmetamorphosed Virginia Formation typically contains between 55 and 65 wt. % SiO_2 , whereas xenoliths contain from 45 to 50. However, gradients in SiO_2 content in the igneous rocks above the xenolith that might track the movement of a partial melt and also explain the $\delta^{18}\text{O}$ gradient are not detected. The absence of SiO_2 gradients may be related to: 1) relatively rapid melt extraction and movement into the surrounding magma due to buoyancy, 2) homogenization in the magma due to convection, 3) destruction caused by thermal perturbations resulting from later magma pulses. Modeling of SiO_2 transport into the surrounding melt via diffusion alone indicates that an initial SiO_2 gradient could be homogenized within a maximum time of 10,000 years. We interpret the $\delta^{18}\text{O}$ profile at the top of the xenolith as being due to retrograde ^{18}O -exchange (i.e. developed after the extraction of a granitic melt from the xenolith and homogenization of the enclosing magma). Diffusion modeling indicates that a retrograde oxygen isotopic exchange profile could be established in as little as 100 to 500 years, assuming an oxygen diffusivity of $\sim 3 \times 10^{-8} \text{ cm}^2/\text{sec}$.

The very different isotopic profiles developed at the upper and lower contacts of the xenolith correlate with distinct differences between composition and mineralogy of the igneous rocks. The upper unit is marked by higher TiO_2 and SiO_2 contents, and Fe/Mg ratio relative to the unit below the xenolith (Fig. 2). This unit is an evolved norite to gabbro-norite that is the most frequently mineralized rock type in the Partridge River intrusion. In contrast the lower igneous unit is a more primitive troctolite with only sparse sulfide mineralization. The well developed oxygen and sulfur isotopic profiles in the

gabbro-norite are indicative of the preservation of a primary xenolith-magma interface. Isotopic values at the lower contact are indicative of a secondary interface. Geochemical data suggest that the troctolitic magma was a later pulse that may have intruded after sulfur and oxygen isotopic equilibration with mafic liquids had been established in the xenolith. Alternatively the troctolitic magma may have delaminated a portion of the Virginia Formation that formed the base of a magma chamber. Because of the thinness of the troctolitic magma sheet isotopic gradients did not develop due to rapid cooling.

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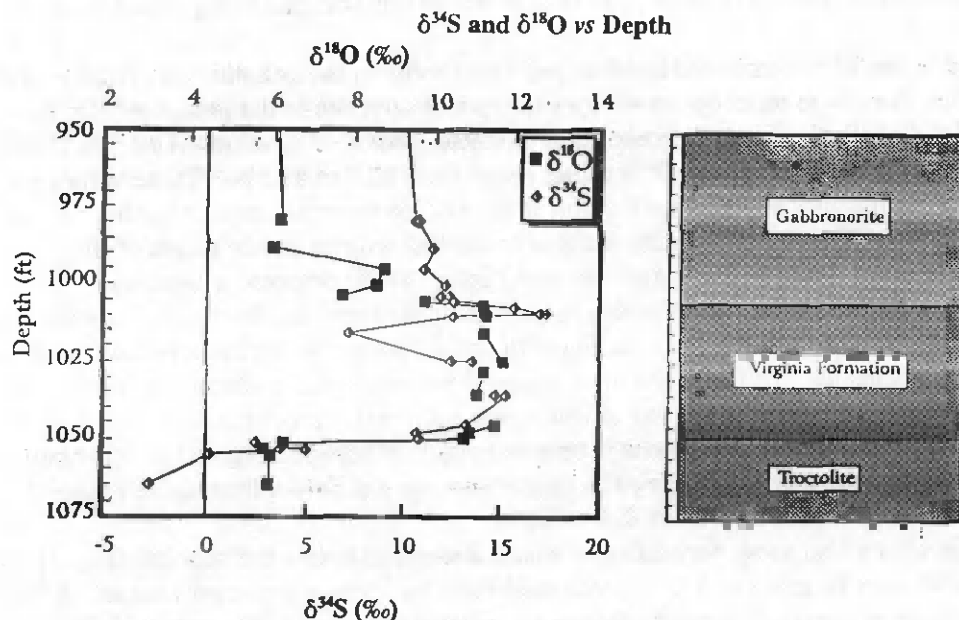


Figure 1. $\delta^{18}\text{O}$ and $\delta^{34}\text{S}$ values through a Virginia Formation xenolith and igneous rocks of the Partridge River Intrusion, drill core B1-127.

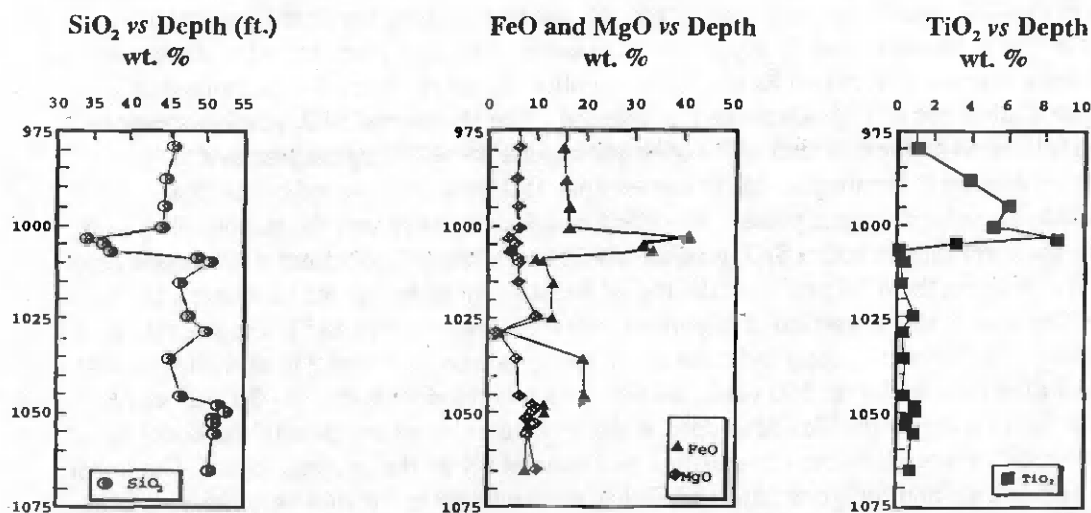


Figure 2. Variations in chemical compositions through xenolith and surrounding igneous rocks, Babbitt area, drill core B1-127.

THE HURONIAN - FROM THE BOTTOM - UP

G. Bennett, Ontario Geological Survey

The Huronian Supergroup is a sequence of Early Proterozoic sedimentary and minor volcanic rocks, up to 12 000 m thick, which lies unconformably upon Archean rocks of the Superior Province. The Huronian belt extends eastward, for about 450 km along the north shore of Lake Huron and into Quebec. The age of the Huronian Supergroup is constrained by the ages of basal volcanic rocks (2.45 Ga) and Nipissing intrusions (2.2 Ga).

The Huronian Supergroup is subdivided, in ascending order, into the Elliot Lake, the Hough Lake, the Quirke Lake and the Cobalt Groups. The Elliot Lake Group contains the only volcanic rocks and important uranium deposits.

The abundance of detrital pyrite and uraninite in the Matinenda Formation, and the general lack of hematite in rocks of the lower three Huronian groups, points to a reducing atmosphere during early Huronian sedimentation. The appearance of hematite in the Cobalt Group marks the accumulation of free oxygen in the Earth's atmosphere (Roscoe, 1968). Studies of Huronian paleosols have also provided valuable insight into the evolution of the Earth's atmosphere (References in Bennett et al. 1991).

The Huronian volcanic rocks, the East Bull Lake Suite (EBLS) of layered mafic intrusions, and the dikes of the Matatchewan-Hearst swarm are an essentially coeval (circa 2.45 Ga) igneous suite (Peck et al., 1995; Heaman, 1997) emplaced near the base of the Huronian Supergroup. The distribution of EBLS intrusions may form two approximately linear arrays. The northern group includes the Agnew Lake and the East Bull Lake intrusions. A second group of EBLS intrusions extends from near the west end of the Sudbury Igneous Complex, in a southwest direction, along the base of the Huronian Supergroup. These two groups of EBLS intrusions represent magma chambers emplaced under two rift segments which joined just west of the present Sudbury Igneous Complex.

The proposed northern rift segment, which contained the Livingstone Creek Formation and the volcanic rocks of the Thessalon Formation of the Sault Ste. Marie-Elliot Lake area, has been deeply eroded, with deeper erosion (i.e. greater uplift) in the east. The southern rift segment, which contains volcanic rock with pillow structures and much intercalated sandstone and wacke (Card, 1978) was probably at a much lower topographic level during erosion of the northern rift segment. These volcanic sequences may correspond to the "seaward dipping reflectors" of modern continental margins.

Following rifting, there was continued erosion and an eventual subsidence as indicated by the deposition of the arenites and uraniferous conglomerates of the Matinenda Formation. The turbidites of the McKim Formation which overlie the Matinenda Formation, suggest marine encroachment along a foundering continental margin.

It is suggested here that a Huronian continental flood basalt province may once have existed north of the present Huronian belt. If so, at least the southern portion of this proposed CFBP, must have been eroded prior to the deposition of the Matinenda Formation, since the latter has a mainly granitic provenance. The sub-Matinenda disconformity (Bennett et al., 1991) marks this potentially long erosion interval.

Heaman (1997) provides evidence for a mantle plume related, large igneous province at 2.45 Ga which includes the intrusive rocks noted above. The model for the Elliot Lake Group described here, although arrived at independently, supports many of the conclusions of Heaman (1997).

Following rifting and early Huronian magmatic events, post-volcanic Huronian sediments were deposited, either along a passive continental margin, or (less likely) within a continually sinking, intracratonic basin. The cyclic sedimentation of each of the three Huronian groups above the Elliot Lake Group are generally believed to record the advance and retreat of Huronian ice sheets. Each cycle begins with a mainly diamictite sequence (glacial advance), overlain by a marine sequence of mudstones, siltstone or carbonate (glacial loading and marine transgression), followed by a relatively thick arenite sequence (interglacial outwash). The presence of drop-stones in some laminated units of all three groups supports the glaciogenic model by indicating the presence of floating ice (Roscoe, 1968).

The entire Huronian sequence was variably deformed and faulted during several deformational events, some of which preceded the emplacement of Nipissing sills at 2.2 Ga (Card, 1978).

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NATIVE COPPER PRECIPITATION BY FLUID-MIXING, KEWEENAW PENINSULA, MICHIGAN

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Large native copper deposits (about 5 billion kg of refined copper extracted) are hosted by brecciated and amygdaloidal tops of basalt lava flows and interflow conglomerates in the 1.1 Ga Mid-continent rift system along the Keweenaw Peninsula, Michigan. A suite of secondary minerals paragenetically associated with the deposition of native copper includes calcite, epidote, quartz, and prehnite, in addition to a number of other low temperature minerals. Most genetic models for the native copper deposits derive ore fluids from rocks deeper within the rift (e.g., White, 1968; Bornhorst, 1997). Mechanisms for precipitation are more problematic; proposed mechanisms include cooling, fluid-rock interaction via metamorphic reactions and fluid mixing. Cooling alone cannot account for native copper precipitation as copper is likely complexed as Cu^+ (copper chloride), but precipitated as Cu^0 (native copper). High water/rock ratios in the ore zones limit the effectiveness of fluid-rock interaction in accounting for the total mass of native copper found concentrated in ore bodies. Wells (1925) first suggested mixing of dilute waters with ore-bearing fluids as a mechanism for native copper precipitation based on chemical principles. Some 60 years later, Richards and Spooner (1986) revived the idea, and, based on fluid inclusion studies, suggested the mixing of low-temperature, low-salinity fluids with ore-fluids as a mechanism for native copper precipitation. Based on these publications and on a reinterpretation of stable isotope data of Livnat (1983), Bornhorst (1992) proposed that "mixing of ore fluids with resident reduced semi-stratified fluids may have been an important mechanism for precipitation of native copper." Oxidized meteoric waters seem to be eliminated as a possible end-member fluid as precipitation of native copper requires reduction of the ore-fluid.

In order to test the hypothesis of fluid-mixing, a suite of calcite samples was collected for 12 km along the strike of the Kearsarge deposit, the largest basalt-hosted deposit. Samples were from mine rock piles and drill core. Calcites from the Kearsarge deposit have a range of $\delta^{18}\text{O}$ from 20.1 to 11.3 ‰ and $\delta^{13}\text{C}$ from -1.7 to -3.1 ‰, based on 39 analyses from this study and 16 from Livnat (1983). The temperature of calcite (and accompanying native copper) deposition is constrained by the assemblage of gangue minerals; $\delta^{18}\text{O}$ values for coexisting mineral pairs suggest an average temperature of about 215°C (Livnat, 1983). At this temperature (215°C), calculated $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ in equilibrium with calcite ranges from +3.5 to +11.5 ‰ (59 % between 3.8 and 5.8 ‰) and calculated $\delta^{13}\text{C}_{\text{CO}_2}$ ranges from -4 to -1 ‰ (71 % between -1.75 and -3 ‰). For these fluids f_{O_2} and pH is predicted to be an unimportant source of variation to account for $\delta^{13}\text{C}_{\text{CO}_2}$. To explain the data by a uniform ore fluid with assumed $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ of +5.0 ‰ requires a temperature variation of 130 to 260°C; a similar temperature range is required for an assumed uniform carbon in the fluid. The gangue mineral assemblage is rather similar throughout the deposit and does not support such a large range in temperature. In addition, the lack of correlation between $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ and $\delta^{13}\text{C}_{\text{CO}_2}$ cannot be explained by temperature variation alone. However, the data may be interpreted by changing temperature and mixing of two or more fluids. This model can also explain the wide spread in $\delta^{18}\text{O}$ for quartz as reported by Livnat (1983). The end-member ore fluid (represented by most of the data) has a $\delta^{18}\text{O}_{\text{H}_2\text{O}}$

and $^{13}\text{C}_{\text{CO}_2}$ ($\sim\delta^{13}\text{C}_{\Sigma\text{C}}$) of about +5 and -2 ‰, respectively and is consistent with derivation from the rift-filling basalt section. The other fluid cannot be well defined, but has $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ and $\delta^{13}\text{C}_{\text{CO}_2}$ of greater than +11 and less than -3.5 ‰, respectively. This fluid is interpreted as water resident at the site of ore deposition. The data presented here support the hypothesis that fluid-mixing played a role in precipitation of native copper in the Keweenaw Peninsula. Additional studies are in progress to further test the fluid-mixing hypothesis.

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THE DIAMONDFEROUS SIX-PAK ULTRAMAFIC LAMPROPHYRE DIATREME, KENOSHA, WISCONSIN, U.S.A.

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Diamond exploration in the midwestern United States began with the discovery of the Lake Ellen kimberlite in 1971. Early exploration focused on the Upper Peninsula of Michigan, resulting in the discovery of over 20 kimberlite bodies in Iron, Dickinson and Menominee counties. These post-Ordovician intrusives range in size from narrow dikes to diatremes in excess of 20 acres. Diamonds are present in many of the Michigan kimberlites, but to date no economic deposits have been identified.

Further regional exploration identified concentrations of fresh "kimberlitic" indicator minerals in glacial tills in southeastern Wisconsin, where at least six historic diamond finds occurred, including the 21.5 carat "Theresa" stone. Although several major diamond exploration companies have been active in southeastern Wisconsin, the Six-Pak diatreme, discovered by the Crystal Exploration-Ashton Mining Joint Venture, is the only pipe ever reported in this region.

Crystal Exploration Inc. carried out sporadic exploration in southeast Wisconsin from the mid 1980's, and in joint venture with Ashton Mining of Canada Inc. from 1992 through 1995. Target identification concentrated on kimberlitic indicator mineral anomalies and data from public airborne magnetic surveys. In early 1994, Crystal Exploration acquired a little-known airborne magnetic survey which had been flown and later donated to Case Western Reserve University by a major oil company conducting base metal exploration. From the new data, three "kimberlite-style" magnetic targets were recognized and ground checked. Two targets were eliminated as cultural responses. During the spring and early summer of 1994, land acquisition and detailed ground magnetic surveys were completed on the third target and in late August of 1994, the Six-Pak diatreme was intersected in the first of eight exploration drill holes.

The Six-Pak diatreme is approximately 50 acres in size and is located within the outskirts of Kenosha, Wisconsin. Reverse circulation with selective core drilling was used to test the target. Between one and seven, one-ton samples of cuttings were recovered from each hole. A concentrate was generated from each sample, and splits were submitted to Ashton Mining's laboratory facility in Perth, Australia for caustic fusion processing. The remainder of this "mini-bulk" sample was processed through Ashton's one-tonne-per-hour dense media separation plant in Crystal Falls, Michigan.

The upper portions of the diatreme are complex, containing sequences of fossiliferous dolostone and red, bedded arenites which grade into ultramafic breccias at depth. The arenites range up to 80 feet in thickness and contain sparse volcanoclastic fragments and indicator minerals. They may represent true crater-facies rocks or, along with the minor carbonate rocks, they may have formed long after diatreme emplacement.

Beneath these sedimentary rocks, the Six-Pak diatreme consists of fairly uniform ultramafic breccias composed primarily of serpentine, calcite, mica, and various opaques; fresh olivine is not present, and melilite or pseudomorphs after melilite have not been recognized. Angular sedimentary xenoliths are common, ranging up to five feet across. Basement xenoliths are extremely rare. "Autolithic" fragments are present in many samples, but they are difficult to characterize, making facies determinations uncertain. Much of the "diatreme" appears to be hypabyssal in character.

Classification of the Six-Pak diatreme is not straightforward, as there are many similarities between this body and other rock types such as kimberlites and lamproites. However, groundmass mica and spinel compositional trends are inconsistent with both kimberlites and lamproites. The Six-Pak diatreme is best classified as an ultramafic lamprophyre (Rock, 1991) or a "melnoite" using terminology recommended by Mitchell (1994).

Heavy mineral species recovered from processed concentrates include the typical "kimberlitic" indicator minerals Cr-pyrope, low-Cr pyrope, Cr-diopside, picroilmenite, Cr-spinel and zircon. Apatite, rutile, amphibole, barite and celestite are also present, along with a variety of sulphide minerals including pyrite, galena and millerite. The Cr-pyrope garnets range in color from purple through red, and exhibit late-stage etching thought to be produced by interactions with groundwater. These garnets are quite common in the heavy mineral concentrates, and contain up to 6.5 wt% Cr₂O₃; they are believed to be derived from garnet-bearing peridotites. No subcalcic "G10" varieties have been identified.

Orange low-Cr pyrope is also common in Six-Pak concentrates, often strongly etched and skeletal in appearance with deep corrosion sculpture and internal decomposition channels. The average MgO content of these grains is 19.1 wt%, and the range is between 13.9 wt% and 20.6 wt%. Both Cr₂O₃ and TiO₂ are typically less than 1.0 wt%. Most of these garnets are probably derived from the Cr-poor megacryst suite, although the lower MgO values found in some grains suggest that minor eclogitic and granulitic garnets may also be present.

Cr-diopside is rare, appearing as emerald-green anhedral fragments. The diopsides are typically coated with orange-white reaction products and exhibit classic "cockscorn" resorption morphologies. Green amphibole is common, and whereas some of these grains may be crustal, most are probably derived from modally-metasomatized mantle rocks. These amphiboles contain up to 3.0 wt% Cr₂O₃ and some are found as mineral pairs with purple Cr-pyrope garnets.

Picroilmenite is one of the most abundant minerals in the Six-Pak concentrates. It occurs as anhedral fragments with leucoxene reaction coatings and contains between 3.7 wt% and 9.8 wt% MgO. These low MgO values, coupled with extremely low Cr₂O₃ (<0.2 wt%) are supplementary evidence that the Six-Pak is an ultramafic lamprophyre, not an archetypal kimberlite.

Various spinels are present in the heavy mineral concentrates. Some are reasonably Cr-rich, with up to 58 wt% Cr₂O₃ plus appreciable MgO and Al₂O₃. Other spinels include magnetite and titanomagnetite.

Coarse honey-yellow to orange-brown zircon crystals are quite common. These grains are typically anhedral, rarely subhedral, and are mantled by fine-grained reaction products, possibly baddeleyite. A date of 686 MY has been obtained from these zircons using U/Pb techniques (Ashton Mining, unpublished data). This is an unrealistic emplacement age as the diatreme intruded Silurian carbonates; however, the age may represent a significant metasomatic event in the underlying mantle.

Importantly, the Six-Pak lamprophyre is diamondiferous; numerous small diamonds have been recovered through caustic fusion techniques. Most diamonds are sharp-edged octahedra or macles, some showing intricate surficial patterns including growth plates and trigons. Six-Pak does not contain economic concentrations of diamonds, and is unlikely to be the source of the large historic drift diamonds.

The discovery of the Six-Pak diatreme is very significant, as it is the first recorded mantle-sourced diatreme to be identified in the southeastern Wisconsin region. The diatreme is also an enigma as it raises numerous questions regarding the existence of other pipes in the area and their economic potential. Do the large Wisconsin "drift" diamonds have a local source, or are they indeed derived from rocks far to the north in Canada?

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Gravity Aspect as a Tool for Recognizing Crustal Fabric and Structure at Minnesota

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Gravity aspect, the facing direction of gravity gradient, is apparently a sensitive indicator of crustal fabric, one that can aid in the recognition, unmixing and mapping of individual components of composite gravity signatures.

Reported as a compass bearing (0-360), aspect records the direction normal to the strike of gradient. In the case of a potential field like gravity, aspect depicts the bearing direction of a vector that is the sum of all of the horizontal components of gravity features that affect a site. Displayed in HSV (hue-saturation-value) color space, where hue (aspect) is valued in the range 0-360, gravity fabrics can be recognized based on hue, and overlap of gravity fabrics can be recognized as vector-like color summing of component hues. Conveniently, HSV color space also provides a means of comparing gravity aspect (hue) to Bouguer intensity, slope, or curvature (each plotted as gray scale value, with or without shadowing).

At MnDNR, terrain analysis tools such as slope and curvature (1st and 2nd horizontal derivatives) are routinely used to check data sets for idiosyncrasies and artifacts before they are included in a GIS-based information system. Slope and curvature provide an excellent means of recognizing edge artifacts caused by inconsistencies in data handling and reduction. In the case of the Minnesota gravity data set (55,900 points, Chandler and Schaap, 1991), terrain analysis was used to generate slope and curvature maps, and also to generate related maps of aspect, profile curvature, and planform curvature.

The aspect pattern for the Minnesota gravity data set is particularly interesting, because it reinforces several interpretations of pre-existing structure in the Lake Superior region and provides a basis for additional discussion about the geologic history of the crust. Readily apparent are the following:

- 1) Overlapping gravity fabrics can be recognized. As good examples, at least two ancestral gravity fabrics can be recognized beneath the Bayfield basin of the mid-continent rift system. The gravity aspect pattern of the footwall of the Duluth Complex can also be reliably traced to 30-40 km inside the western margin of the complex.
- 2) Gravity aspect can be used as an effective means of delineating the axes of gravity lows and gravity highs. Elongate "hinges" dominate the statewide pattern. Domal or bowl-like aspect patterns are, for the most part, restricted to individual intrusive features.
- 3) A pervasive north-northwest striking gravity fabric is parallel to the magnetic expression of

similarly trending regional dike swarms. The fabric has a much broader "wavelength" than the spacing of the dikes. Curvature profile maxima, as a rough indicator of depth, and a general lack of magnetic expression suggest that this broader fabric may be more deeply rooted than the higher amplitude, more easily recognized gravity fabric of the east-northeast trending greenstone-granite-gneiss terranes that overprint it.

4) Pre-rift gravity fabric is only partly obliterated by the mid-continent rift system in Minnesota.

5) A prominent gravity fabric parallels the northern edge of the Penokean orogen area in Minnesota, but completely interrupts the north-south aspect pattern that can be traced on either side of the interruption. The Penokean area, in general, expresses a complex interplay of fabrics.

The patterns of gravity aspect in Minnesota beg several questions. What is the geologic significance of axial "hinges"? What is the significance of the north-northwest trending fabric, and at what depth within or below the crust does that fabric exist? Can aspect be applied in interpretation of magnetic data? Will additional gravity data increase the signal-to-noise ratio in the aspect pattern so that more subtle features can be resolved? Can algorithms be applied, in conjunction with aspect, to separate component fabrics?

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STRATIGRAPHY, TECTONICS AND MINERALIZATION OF THE SIOUX LOOKOUT
OROGENIC BELT, WESTERN WABIGOON SUBPROVINCE

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Tectono-stratigraphic analysis of the metamorphosed and variably deformed Archean supracrustal rocks of the Sioux Lookout Belt (western Wabigoon Subprovince) suggests the accumulation of lower, older, subaqueous basalt successions (Stages 1, 2), capped by sequences of more felsic volcanoclastic rocks (Stages 3, 4), with minor lavas and porphyries (at or near small volcanic centres), overlain by upper sedimentary rocks (Stage 4), such as turbidite deposits, which were influenced by synchronous intermediate-felsic volcanism (interbedded tuffs, volcanic pebble conglomerate, magnetite iron formation). Minor volcanogenic sulphide mineralization and sub-exhalite hydrothermal alteration are uncommon in the volcanoclastic rocks. A relatively small (3 km thick) andesitic stratovolcano succession and its comagmatic subvolcanic intrusion (Stage 3, but undated) are well preserved, but no epithermal mineralization and only insignificant amounts of porphyry copper-type mineralization have been found.

Northwest-southeast compression segmented the original basin (arc volcanics on basalt, buried and flanked by younger volcanic detritus) into an imbricate stack of numerous thrust slices that generally dip and young to the southeast (Stage 5, a foreland-vergent fold-and-thrust belt). Fluvial polymict conglomerates accumulated in a narrow, linear (strike-parallel), intra-orogenic "molasse" basin and were overthrust by older volcanic rocks forming the bases of thrust slices (relative ages confirmed by published U-Pb zircon dates). A large volume of basaltic strata (Northern Volcanic Belt) was overturned adjacent to the microcontinental Winnipeg River Subprovince foreland; the overturning was likely produced by large-scale faulting (hypotheses include: a Laramide-type uplift, or flower structures in cross-sectional views of strike-slip to oblique-slip faults). The major faults appear to be sinistral strike-slip faults (Stage 6), some of which may be reactivated thrust faults (i.e., Stage 6 superimposed on Stage 5). Granitoid plutons intruded along some of these major faults. Late stage sinistral-sense motions produced features such as a pull-apart basin (20 km-long Patara Fm.), releasing bend plutons, and tension gashes. Quartz veins appear to be thicker and more abundant, and contain more gold, near the major deformation zones (thrust and/or strike-slip faults). At a regional scale, gold occurrences appear to be located along lineaments which resemble Riedel shear fracture systems.

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PRELIMINARY INVESTIGATIONS OF THE PICK LAKE DEPOSIT, WINSTON LAKE MINE, ONTARIO: A REMOBILIZED MASSIVE SULPHIDE OREBODY

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The Winston Lake mine is situated in lower amphibolite-facies, calc-alkalic rocks of the Neoarchean Schreiber-Hemlo greenstone belt. It comprises several volcanogenic massive sulphide (VMS), zinc-copper deposits:

Deposit	Ore (all categories) (million tonnes)	Metal Grades				Dilution* (%)
		Zn (%)	Cu (%)	Ag (g/t)	Au (g/t)	
Winston Lake	3.1	15.90	1.00	30.3	1.02	20
Pick Lake:						
Upper + Middle	0.26	11.21	0.77	31.5	0.65	30
Lower	1.2	15.90	0.86	38.0	0.46	25

(* n.b. Possible category of Pick Lake is non-diluted)

The Pick Lake deposits occur within strongly foliated, felsic to intermediate volcanoclastic rocks, approximately 1.3 km southwest of the Winston Lake deposit, and 1 km lower in the footwall stratigraphic succession. The deposits are thin, but continuous, massive sulphide sheets with a down-plunge length of approximately 1000 m. The Upper and Lower zones average approximately 2.0 and 4.0 m in thickness, respectively. Massive sulphide ore, in sharp contact with its host rocks, has a strike length which varies from 100 m to 400 m. It forms a dyke-like body which locally crosscuts both foliation and granitic dykes.

Despite similar metal grades and mineralogy (sphalerite, pyrrhotite, pyrite, chalcopyrite), sulphide textures in the Winston Lake and Pick Lake deposits are markedly different. Finer-grained Pick Lake ore is characterized by the ubiquitous development of *durchbewegung* texture, in which brecciated wall-rock xenoliths comprise 10 to 15 % of the massive sulphide. Xenoliths, generally ranging in size from <1 mm to 10 cm, are typically: (1) sub-rounded grains of quartz $\pm$ feldspar, sericite; (2) tabular crystals or aggregates of biotite $\pm$ chlorite, amphibole; or (3) sub-rounded granitic dyke fragments. They may be kinked, folded and/or aligned parallel to one another and with sulphide banding. Large (>1m) rafted host rock xenoliths are also apparent.

Piercement cusps and injection structures are developed where massive sulphide has migrated into folded and boudinaged host rocks.

The nature and scope of these secondary textures at Pick Lake are characteristic of large-scale sulphide remobilization, subsequent replacement and annealing. The flowage of massive sulphide, arising from substantial competency contrasts between competent silicate xenoliths and incompetent sulphides during deformation (Marshall and Gilligan 1989), has resulted in widespread durchbewegt ore. The high degree of remobilization at Pick Lake may be the result of the deposit's proximity to the Winston Lake granite (averaging 40 m) and the development of high strain zones and hydrothermal fluids in the contact aureole. Crosscutting relationships demonstrate that remobilized sulphide deposition postdated the intrusion of granitic dykes, perhaps 35 million years after the presumed primary VMS deposition (ca. 2720 Ma). The location, size and characteristics of the primary sulphide deposit(s), from which the enigmatic Pick Lake ore was derived, are as yet unknown.

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REVISITING THE DISAPPEARANCE OF THE HURONIAN IN THE SUDBURY-CRERAR AREA: INSIGHT FROM THE GEOCHEMISTRY OF AMPHIBOLITES AND PARAGNEISSES

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The presence of high grade metamorphic equivalents of Huronian Supergroup (Sgp.) and Nipissing Suite rocks in the Grenville Front Tectonic Zone (GFTZ) in Ontario has been long debated. A 5 km wide zone south of the Grenville Front in the Sudbury-Coniston-Crerar area provides an opportunity to test this suggestion geochemically. In addition to containing a variety of amphibolites, quartzites and muscovite-kyanite-bearing metapelites, the area is well mapped and covered by a database of some 155 chemical analyses, including 80 major element analyses by Kwak (1967), Pearson (1959) and LaTour (1979), as well as 75 newly acquired major and trace element analyses (Easton, unpublished). Roughly 80 of these analyses are of amphibolites, with another 60 representing paragneisses.

Amphibolites: Two main amphibolite types are recognized in the field: migmatitic amphibolites, typically garnet-bearing, and non-migmatitic, locally diabasic textured, typically clinopyroxene-bearing, amphibolites. Geochemically, all datasets show 3 similar groups of amphibolites (Fig. 1a); from most to least abundant, these are: (1) a tightly clustered high-Fe tholeiite group corresponding to the migmatitic amphibolites. (2) a magnesium-rich group with $Mg\#70-78$, $MgO=7.7-13.1\%$, and $CaO=10.8-14.5\%$. Pods of orthopyroxene hornblendites in the area may be related to this group, and (3) a high-Mg tholeiite group, with $Mg\#=54-59$, $MgO=7-9\%$, and $CaO=9.6-10.5\%$. Both groups 2 and 3 show relict differentiation trends within individual bodies (Fig. 1a). In the field, group 3 corresponds to diabasic-textured rocks previously interpreted as Nipissing diabase; and chemically, it lies in the field of Nipissing diabase cluill margins. In the field, group 2 amphibolites locally show diabasic textures, but more typically are black, thinly layered rocks, with associated gabbroic anorthosite. Chemically, group 2 corresponds to gabbroic cumulate rocks of the Nipissing suite. Group 2 or 3 amphibolites show no clear chemical similarities with plutons of the Huronian magmatic suite (e.g. River Valley anorthosite). Consequently, group 2 and 3 amphibolites are interpreted as equivalents of the 2.2 Ga Nipissing suite. Group 1 amphibolites plot in the field of Archean and Huronian metavolcanic rocks.

In the Southern Province, Nipissing suite rocks with $Mg\#=54-59$ predominate, whereas, in the GFTZ, those with high $Mg\# (>70)$ are most common, as is interlayered gabbroic anorthosite. One explanation is that in the GFTZ, we see the mid-crustal "auxiliary" magma chambers of the Nipissing suite, postulated by various workers, which would be dominated by mafic and anorthositic cumulate rocks. If so, this leads to speculation that migmatization of the country rocks may be related to wall rock-magma chamber interaction. It is still unclear if these magma chambers are hosted in Archean or Paleoproterozoic rocks.

Paragneisses: Kyanite-bearing gneisses fall into two chemical groups (Fig. 1b). Most are intermediate composition micaceous gneisses with $SiO_2=57-64\%$, $Al_2O_3=19.9-26.8\%$, $TiO_2=1.2-1.8\%$, $Fe_2O_3=4.5-8\%$ and $CIA=73-83$. Chemically, these rocks are most likely of sedimentary derivation. Garnet-biotite gneisses spatially associated with the kyanite gneisses have similar chemistry, apart from lower Al_2O_3 contents (13-18%) and higher MgO and CaO contents (Fig. 1b). The second group of kyanite gneisses is characterized by high Fe_2O_3 contents (10-12%), varied Al_2O_3 content (12-30%), and high Cr, Ni, V and Ti contents. The origin of these kyanite gneisses is unclear, although derivation from altered metavolcanic rocks is possible on the basis of field relationships and trace and REE abundances.

Many of the garnet-biotite gneisses have trace element signatures similar to those of intercalated garnet amphibolites, and could represent intermediate to felsic volcanic rocks or volcanoclastic sediments. Some of the garnet-biotite gneisses have pronounced positive Ce anomalies (Fig. 1c), suggesting exposure to an oxidizing environment. Similar anomalies are common in weathering profiles, and it is possible some of the garnet-biotite gneisses represent a weathering profile developed on older metavolcanic rocks. No rare earth element studies have been conducted on any Huronian weathering profiles, so it is unknown if Huronian

regoliths possess similar cerium anomalies.

Both the kyanite and garnet-biotite gneisses are associated with quartzose gneisses ($\text{SiO}_2 > 74\%$), quartzites, which locally show relict transposed bedding, and rare conglomerate horizons. Typically, quartzites have higher Fe_2O_3 and TiO_2 contents than do any of the Huronian quartzitic or conglomeratic units (Fig. 1b), however, derivation of the metasedimentary gneisses from volcanic-derived sediments such as those in the Elsie Mtn. and Stobie formations is not precluded. In one instance, a kyanite gneiss and associated quartzite show REE patterns similar to those present in the Pecors and McKim formations (Fig. 1d).

Based on field relationships and geochemistry, it is most likely that the paragneisses and associated garnet amphibolites in the GFTZ in the Sudbury-Crerar area are derived from both an Archean metasedimentary-metavolcanic succession and high grade equivalents of the Paleoproterozoic Elliot Lake Group.

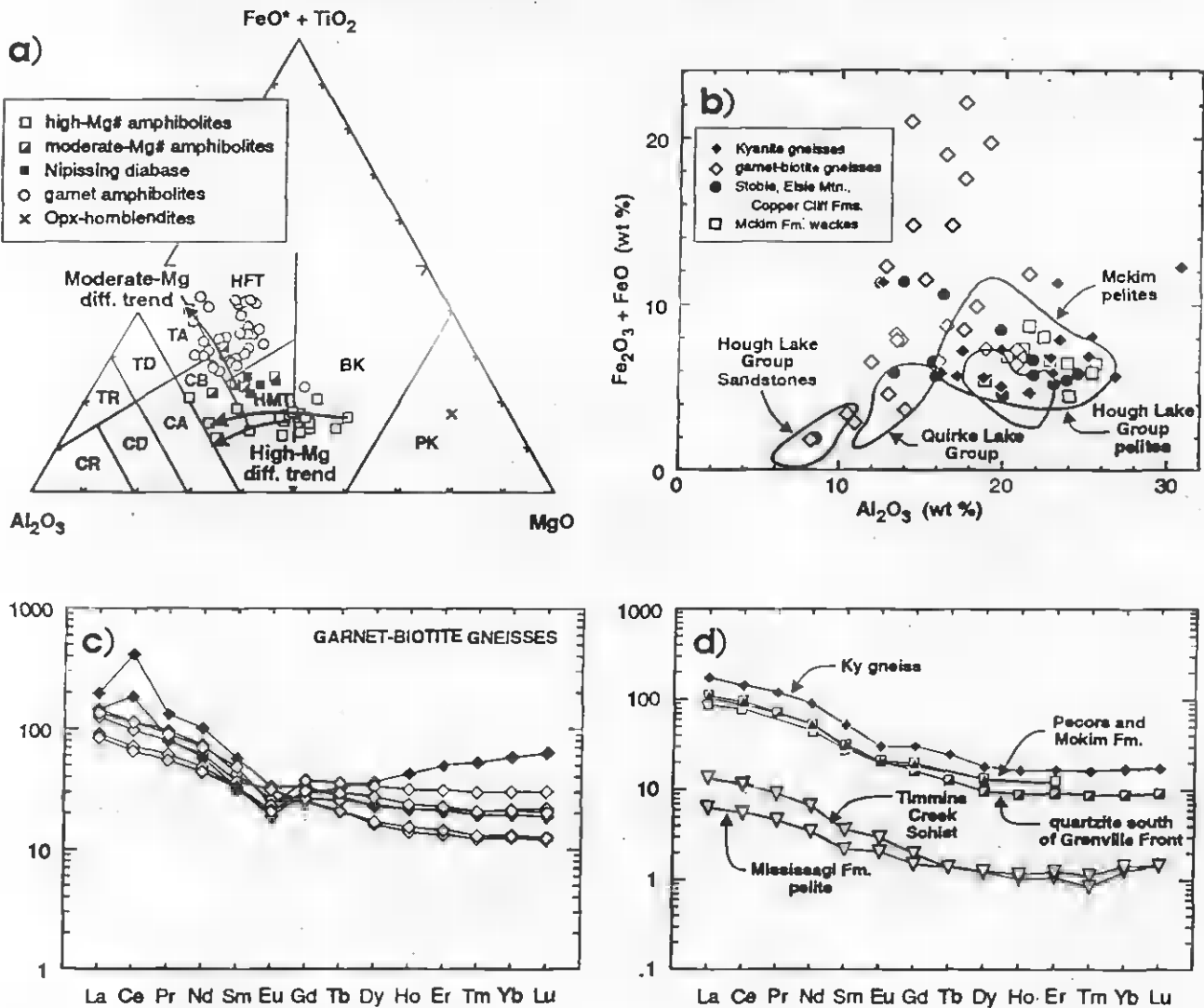


Figure 1: Geochemical characteristics of amphibolites and paragneisses from the Sudbury-Crerar area. Data from Kwak (1967), Pearson (1959), LaTour (1979) and Easton (unpublished). A) Jensen plot showing three main groups of amphibolites. Arrows indicate differentiation trends in individual bodies. B) Plot of total iron versus Al_2O_3 for Street Twp. paragneisses and lower Huronian Sgp. units. C) Chondrite normalized REE plot of gt-bi gneisses from Street Twp. showing +ve cerium anomalies. D) Chondrite normalized REE plot of Huronian Sgp. units and metasedimentary rocks south of the Grenville Front.

Space-time patterns of Early Proterozoic post-Penokean (1800-1600 Ma) metamorphism and cooling in the southern Lake Superior region

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Introduction. The Precambrian terrane of the southern Lake Superior region has experienced a protracted Proterozoic history from accretion/collision during the Early Proterozoic Penokean orogeny to aborted cratonic rifting at 1100 Ma. Recognition and characterization of post-orogenic metamorphism, cooling, and thermal resetting is essential for understanding the evolution from active accretion/collision to development of a stable craton (Rogers et al., 1984, *Geology*). In this regard, considerable advances have been made since the excellent overview of Precambrian metamorphism by Geiger and Guidotti (1989, *Geoscience Wisconsin* v. 13). We summarize here important differences in the nature and extent of Early Proterozoic post-Penokean (1800-1600 Ma) thermal histories between different portions of the exposed orogenic belt (i.e. central Minnesota, northern Wisconsin, and northern Michigan) and speculate that some of these differences may reflect initial differences in the metamorphic grade (namely pressure) attained during the Penokean Orogeny.

Central Minnesota. Penokean-age metamorphism in Minnesota increases from subgreenschist facies in the north to amphibolite facies in the south near the first appearance of Penokean-age plutonic rocks (Morey, 1978, GSC Paper 78-10). New thermochronologic and thermobarometric data from rocks of the internal zone of the Penokean orogen in central Minnesota indicate that the Early Proterozoic sediments were metamorphosed twice - initially during the Penokean Orogeny (1870-1820 Ma) and again during an episode of post-orogenic magmatism at 1770-1760 Ma (Holm and Lux, 1996, *Geology*; Darrah et al., 1996, *ILSG*). Thermobarometric results (Labotka et al., 1981, *GSAA*; Holm and Selverstone, 1990, *Geology*; Darrah et al., 1996) indicate ~6 kbar paleopressures for both metamorphic events suggesting little crustal uplift during the intervening period. The 6 kbar pressure estimates for the 1770-1760 Ma staurolite grade metamorphism in Minnesota, the midcrustal (13-15 km) emplacement depths of the post-tectonic plutons, and the complete lack of any Penokean-age hornblende Ar/Ar dates from the area (Darrah et al., 1996) argues against a simply contact related metamorphism adjacent to mid-or shallow crustal plutons. Instead, increased heat-flux at the base of the crust in the thickest portion of the orogenic belt (the internal zone) was responsible for both partial melting of the lower crust and regional metamorphism to staurolite grade of the middle crust. The midcrustal rocks underwent rapid exhumation shortly after intrusion and metamorphism and may have even been exposed before 1700-1650 Ma (based on the probable age of the Sioux Quartzite in southwest Minnesota, Chandler and Morey, 1992, *USGS Bulletin* 1904-N). The 1770-1760 Ma metamorphism, intrusion, and rapid exhumation of the internal zone of the Penokean orogen probably represents orogenic collapse and was the last major 'event' to have affected this region aside from the final formation of the McGrath gneiss dome around 1700 Ma (Holm and Lux, 1996).

Northern Wisconsin and northern Michigan. Uniform Early Proterozoic metamorphic pressures from the internal zone in central Minnesota are greater than the typical 2-4 kbar paleopressure estimates for Penokean metamorphism throughout most of Wisconsin (Geiger and Guidotti, 1989). In contrast metamorphic nodal patterns in northern Michigan are superposed on low-grade greenschist metamorphism. The origin of the prominent nodal metamorphic patterns has been one of the most interesting questions in geologic research of the area. Pressure differences among the nodes (4 kb at Peavy, 2 kb at Republic and 7 kb at Watersmeet) probably reflect initial differences in crustal thickness attained during the Penokean Orogeny (Attoh and Klasner, 1989, *Tectonics*) although for at least the Watersmeet area, the uplift and doming of the isograds occurred significantly later (at ~1755 Ma; Schneider et al., 1996, *CJES*). Emilio et al. (1996, *Eos*) have recently suggested that the mapped nodal pattern at Peavy is actually a simplification of a more complex polyphase metamorphic history characterized by possibly three discrete metamorphic events.

The extent and nature of ~1760 Ma metamorphism within the Penokean orogen in Wisconsin is just beginning to be unraveled. Van Wyck (1995, UW-Madison Ph.D.) illustrated a thermal disturbance adjacent to an ~1760 Ma pluton in central Wisconsin and Romano et al. (1997, *GSAA*) obtained evidence for partial thermal resetting interpreted to be related to ~1760 Ma magmatism in west-central Wisconsin.

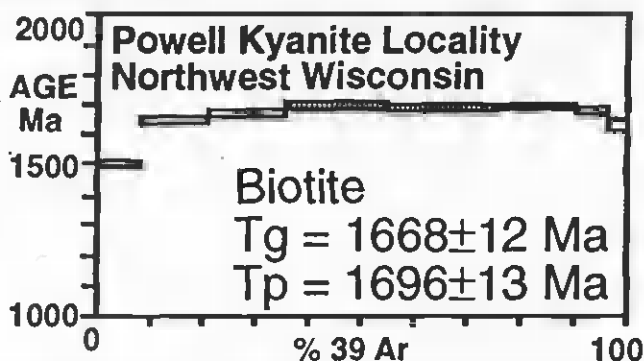
However, these disturbances appear to be a more localized contact-related phenomenon because several localities in Wisconsin (and upper Michigan) yield hornblende Ar/Ar dates that reflect cooling from Penokean-age metamorphism (i.e., 1800-1850 Ma; Schneider et al., 1996; Romano et al., 1997; Mancuso et al., 1997, ILSG). This interpretation is also consistent with the ~1760 Ma granites in northwest Wisconsin having been emplaced at somewhat shallower (9-11 km) depths than similar age granites in central Minnesota (Anderson et al., 1980, CMP).

The timing of unroofing of the post-tectonic granites in northern Wisconsin is poorly constrained but probably occurred fairly shortly after intrusion. In northwest Wisconsin, an area little affected by later reheating and deformational events, biotite cooling dates (both Rb/Sr and Ar/Ar) are 1700-1730 Ma (Peterman and Sims, 1988, Tectonics; see spectrum below). Also, the 1760 Ma Radisson granite in this area is overlain by the undeformed Barron Quartzite which, if correlatable with the Sioux Quartzite (Chandler and Morey, 1992) might indicate exposure by about 1700 Ma.

Precambrian rocks in Wisconsin and northern Michigan were also affected by younger Early Proterozoic events. These include possible contact metamorphism at ~1720 Ma in northern Michigan which may have created the Republic metamorphic node (Schneider et al., 1996), a cryptic 1720 Ma metamorphic event in Wisconsin (Van Wyck, 1995) and the widespread but little understood 1630 Ma low-grade event which affected rocks throughout much of Wisconsin and perhaps portions of northern Michigan. The absence of these younger overprinting events in areas such as central Minnesota, northwest Wisconsin and portions of northern Michigan (i.e., Watersmeet) allow us to learn much about the earliest and extremely important post-Penokean metamorphic/plutonic event at 1770-1760 Ma.

Implications. Based on the above overview, it appears that the nature and extent of post-Penokean Early Proterozoic metamorphism and cooling is distinctly different within different parts of the orogenic belt. We note that the 1770-1760 Ma post-tectonic plutons have deeper emplacement depths in areas where the Penokean paleopressure estimates are greater (i.e., central Minnesota compared to northern Wisconsin). This suggests that little unroofing of the Penokean orogenic belt occurred prior to ~1770 Ma but that significant (and variable) amounts of unroofing occurred rapidly thereafter (~10 km of unroofing in northern Wisconsin between 1760 Ma and 1700 Ma but 15-20 km during the same time span for central Minnesota). We speculate that the differences may reflect initial differences in the amount of crustal thickening attained across the Early Proterozoic orogen. Post-orogenic metamorphism appears to have been more pervasive in central Minnesota (reaching staurolite grade) perhaps because crustal thickening was greater there than in the island arc terrane of Wisconsin (Geiger and Guidotti, 1989).

Knowledge of the complete Early Proterozoic unroofing history of the Penokean orogenic belt is critically dependent on the age of the quartzites mentioned above. If they are indeed Early Proterozoic in age (as seems to be suggested by paleomagnetic data, by ages of detrital zircons in other quartzites of the region, and by the fact that some were probably deformed at 1630 Ma) then these quartzites may represent stabilization of continental crust in the Lake Superior region after a protracted history of tectonic instability which lasted hundreds of millions of years (Greenberg and Brown, 1983, J. Geology). It appears that the sudden and rapid collapse of the overthickened Penokean orogen together with thermal re-equilibration of the lithosphere was a critical step in crustal stabilization during the Early Proterozoic (Rogers et al., 1984; Nelson, 1991, GJI).



Complete citation of references will be available at the presentation and upon request (dholm@kent.edu).

Results of Ar/Ar dating of dikes in central Minnesota and the Minnesota River Valley

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Late- and post-tectonic (1820-1770 Ma) magmatic suites of central Minnesota are crosscut by mafic dikes that generally trend northeast-southwest to east-west. Much of the region affected by the Penokean orogeny, including central Minnesota, Wisconsin, and the upper peninsula of Michigan, is crosscut by similar late northeast-trending mafic dikes (King, 1990, CJES; Chandler, 1993, in USGS Prof. Paper 1556). Some of these dikes are certainly related to 1100 Ma mid-continent rift magmatism (Green et al., 1987, in GAC Spec Paper 34). However, some are also significantly older and appear related to the ~1770-1760 Ma magmatic suite. In Wisconsin, northeast-oriented mafic dikes that crosscut ~1770 Ma plutons were metamorphosed to amphibolite facies at ~1720 Ma (Van Wyck, 1995; UW-Madison Ph.D. thesis). In addition, in central Minnesota Pb isotope data from the mafic dikes are consistent with a ~1800 Ma age suggesting that the dikes may have intruded only shortly after emplacement of the ~1770-1760 Ma magmatic suite (Horan et al., 1987, Prec. Res.). Mafic dikes of Early Proterozoic age have also been reported from the Minnesota River Valley (Hanson and Himmelberg, 1967, GSAB).

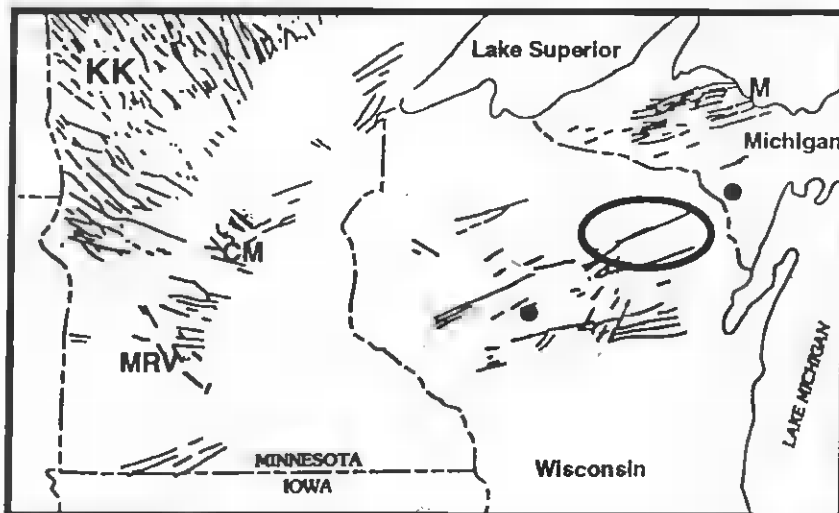
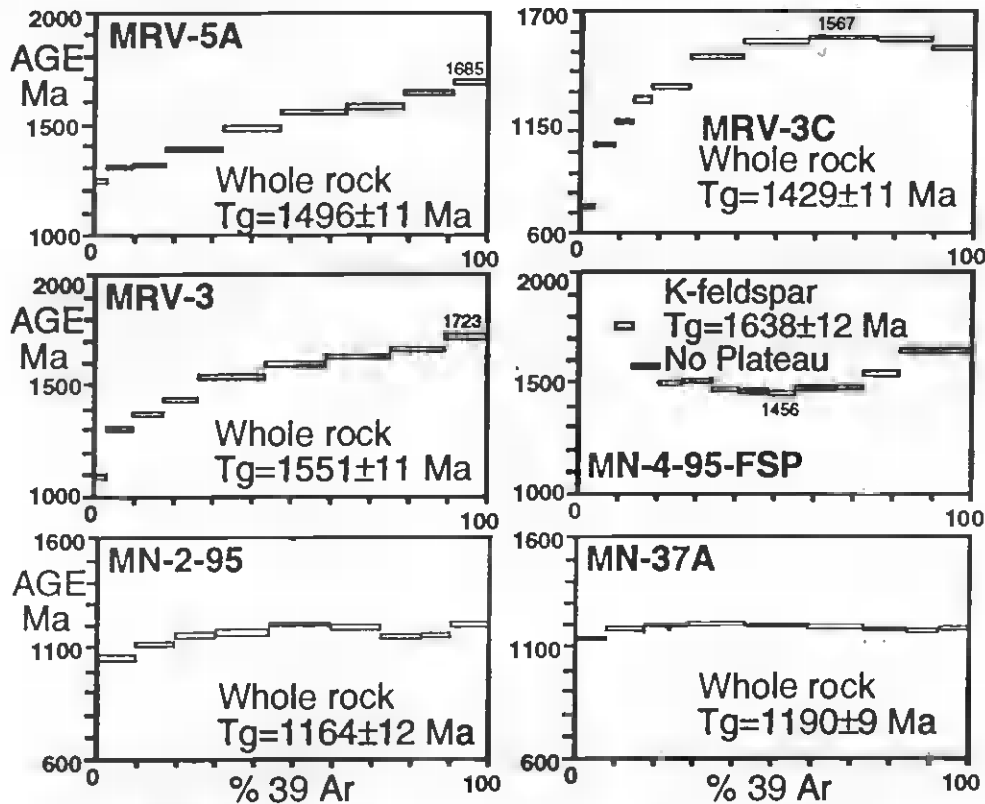
We dated three whole-rock samples (MRV-5A, MRV-3C, and MRV-3) of andesite dikes from the Granite Falls area, Minnesota River Valley (Himmelberg, 1968, MGS Pub.) using the Ar/Ar incremental heating technique. No plateau dates were obtained. Rather, all three spectra display significant Ar loss profiles and their total gas dates (1429-1551 Ma) are therefore meaningless. The oldest increments for the three samples (1567 Ma, 1685 Ma, and 1723 Ma) are somewhat younger than the K-Ar mineral (hornblende and biotite) dates of 1690-1930 Ma obtained on andesite dikes near Granite Falls by Hanson and Himmelberg (1967). Because of the Ar loss indicated by the spectra, the oldest increments we obtained should be considered minimum dates for intrusion of the dikes. This is consistent with the fact that at least one andesite dike in this area is intruded by an ~1850 Ma pluton (granite of section 28; Goldich et al., 1970, GSAB).

We dated two whole rock samples of northeast trending basalt dikes which cross-cut 1770 Ma granites near St. Cloud. Although neither sample displayed a plateau date (MN-2-95 and MN-37A), the spectra are considerably less disturbed and the total gas dates substantially younger (1150-1200 Ma) than those obtained from the Minnesota River Valley. Feldspar separated from a quartz-feldspar porphyry dike in the same area yielded a distinct saddle-shaped spectra indicative of excess argon. In this case the age minimum of 1456 Ma for this spectra would represent a maximum age for intrusion of the dike. Our Ar/Ar whole-rock basalt dates from the St. Cloud area are significantly younger than the three whole-rock basalt K-Ar dates of 1280 Ma, 1460 Ma, and 1570 Ma obtained from this area by Hanson (1968, MGS Rept. Inv. 8). Those dates have commonly been interpreted as partially reset dates and the Pb isotope data of Horan et al. (1987) seem to support that interpretation. However, we interpret our results from the mafic dikes (MN-2-95 and MN-37A) as indicating that some of the northeast-oriented dikes in the St. Cloud area are Keweenawan in age. We note that the morphology of the dike spectra from the two areas (MRV and CM) are dramatically different and this probably reflects a difference in their intrusion ages and post-intrusion histories.

Our interpretation that Keweenawan dikes were intruded outside of the main rift trough in central Minnesota does not seem unreasonable given the evidence for Keweenawan dike swarms in northern Michigan (Baraga-Marquette) and in central Wisconsin (Green et al., 1987; King, 1990). Indeed, Chandler (1993) inferred on the basis of position and similarity of strike that the central Wisconsin dike swarm may correlate with the northeast-striking dike swarm in central and southwestern Minnesota. We conclude that there are probably two northeast-oriented dike populations in central Minnesota: an older Early Proterozoic population that probably intruded very shortly after intrusion of the 1770 Ma post-tectonic granites and a younger population associated with Keweenawan rift magmatism.

Intrusion of Keweenawan dike swarms throughout the Lake Superior region may cause at least localized thermal overprinting and complications of the older Early and Middle Proterozoic regional thermal patterns. Schneider et al. (1996, CJES) reported Keweenawan disturbances of Ar/Ar spectra in northern Michigan and Romano et al. (1997, GSAA) obtained a Keweenawan Ar/Ar biotite date from west-central Wisconsin possibly related to dike resetting. The locus of <1.2 Ga Rb/Sr biotite dates mapped in northeast Wisconsin (the Goodman Swell) has been attributed to uplift associated with loading

along the Keweenaw rift trough (Peterman and Sims, 1988, Tectonics). We suggest that Keweenaw dikes and associated plutons at depth, if pervasive enough, may provide an alternative explanation (see also Coakley and Wang, 1992, Eos).



Dike swarms in the Lake Superior region (after Chandler, 1993). CM is central Minnesota, MRV is Minnesota River Valley, KK is Kenora-Kabetogama dike swarm, M is Marquette. Filled circles are Keweenaw biotite dates and large ellipse encloses region of Rb/Sr biotite dates (Goodman Swell of Peterman and Sims, 1988).

The Evolution of the Hydrothermal Systems Associated with the Sturgeon Lake Caldera Complex, Northwestern Ontario

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The Archean Sturgeon Lake Caldera Complex (SLCC; Morton et al., 1990) is located within the Wabigoon volcano-sedimentary greenstone belt approximately 200 Km northwest of Thunder Bay, Ontario. The Complex is host to 6 known massive sulfide orebodies and numerous subeconomic massive sulfide lenses. Combined, these orebodies produced nearly 18.4 million tons of ore grading 8.5% Zn, 1.06% Cu, 0.91% Pb, and 3.73 ounces per ton Ag between 1971 and 1991.

Based on detailed mapping, core relogging, petrographic investigations, and evaluation of whole rock and trace element lithogeochemical analyses, the caldera complex has been divided into three distinct volcanic sequences (Hudak, 1996). The Pre-Caldera Sequence (PCS) represents a large, dominantly subaerial shield-type basalt volcano with localized fields of subaerial to shallow subaqueous basaltic tuff and cinder cone deposits (Groves et al., 1988). The Early Caldera Sequence (ECS) represents the onset of explosive felsic volcanism and the formation of the major caldera structure. The ECS comprises laterally extensive (up to 16 km along strike) and locally very thick (up to 900 m) mesobreccia and megabreccia deposits interlayered with and overlain by a series of shallow subaqueous (<1000 m deep) quartz-phyric pyroclastic flow deposits (up to 1200 m thick) which host the F-Group and Mattabi massive sulfide orebodies. The Late Caldera Sequence (LCS) represents the change in volcanic style from dominantly explosive to passive eruptions. The stratigraphic section in the LCS progresses from quartz $\pm$ feldspar-phyric pyroclastic flow deposits (which host the Sturgeon Lake, Lyon Lake, Creek Zone and Sub-Creek Zone orebodies) through subaqueous andesite and dacite lava flows and domes to the formation of thick sequences of volcanoclastic sediments and chemical sediments which include iron formation. Age dates of the caldera-associated volcanic rocks (Davis et al., 1985), as well as trace element evidence (Campbell et al., 1981), suggest that the Beidleman Bay Intrusive Complex (trondjemite to quartz diorite) was the subvolcanic magma chamber for the eruptive material.

The style of hydrothermal alteration also evolved during the development of the SLCC. Two distinct hydrothermal alteration suites have been identified: a) an assemblage associated with massive sulfide mineralization early in the development of the SLCC; and b) an assemblage associated with iron formation which formed during the later stages of the SLCC. Detailed mapping indicates that both alteration suites illustrate semi-conformable geometry with localized "pipe-like" geometry near synvolcanic fault zones.

The massive sulfide associated alteration suite contains the following mineral assemblages: a) aluminum silicate (andalusite/kyanite $\pm$ pyrophyllite, sericite); b) aluminum silicate + chloritoid (andalusite/kyanite + chloritoid $\pm$ Fe-rich chlorite, pyrophyllite, sericite); c) sericite $\pm$ pyrophyllite; d) chloritoid + Fe-rich chlorite/Fe-rich carbonate; e) Fe-rich chlorite $\pm$ Fe/Mg-carbonate; and f) localized zones of secondary feldspar + Mg-rich chlorite.

The iron formation associated alteration suite contains the following mineral assemblages: a) Fe-rich chlorite + garnet + magnetite + Fe-rich carbonate $\pm$ grunerite; b) chloritoid + Fe-rich chlorite $\pm$ Fe-rich carbonate; and c) Fe-chlorite + Fe-carbonate $\pm$ sericite.

There appears to be a change in the style of alteration in the caldera complex from early, high temperature base-metal sulfide producing hydrothermal systems to later, lower temperature Fe-formation

producing hydrothermal systems. The change in alteration style appears to be temporally associated with the change from pyroclastic to passive volcanism.

The Cu-Zn orebodies associated with the SLCC may be Archean examples of "High Sulfidation" volcanogenic massive sulfide deposits as described by Sillitoe (1995), Sillitoe et al., (1996), and Gamo et al. (1997). The massive sulfide associated alteration assemblages may have formed, in part, by reactions between originally glass-rich volcanoclastic rocks and pulses of metal-rich, magmatic fluids which were transported from the top of the Beidleman Bay intrusion to the seafloor in synvolcanic structures during the early stages of caldera development. Mineralization appears to have occurred directly beneath the seafloor by sulfide replacement of the strata. The iron formation alteration assemblages resulted from metasomatism by hydrothermal fluids composed of evolved seawater which occurred at increasingly lower temperatures as the Beidleman Bay intrusion continued to cool and magmatic volatiles were less abundant.

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Patterns of structure and metamorphism in the Hemlo greenstone belt.

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Hemlo greenstone belt rocks generally possess a well-developed (strong) penetrative planar fabric that is variably defined by combinations of mineral foliation, shape foliation, metamorphic layering, and compositional layering. In map view the trajectories of this fabric are curvilinear and generally strike subparallel to bounding granitoid masses and larger internal plutons. Within the plane of the strong fabric, stretch, mineral, and crenulation lineations are common. Stretch and mineral lineations tend to be subparallel in a given area; crenulation lineations may or may not be subparallel to the stretch and mineral lineations. Lineations have notable variation in orientation although there is a general westward component to their plunges. Internal and external granitoid bodies show variable degrees of fabric development. Marginal phases of the Pukaskwa and Black Pic batholiths exhibit strong fabrics near the granite-greenstone belt contact. The Dotted Lake pluton has a well-developed fabric near its margin that decreases in intensity toward its interior. In contrast, the Heron Bay Pluton appears to be weakly to non-foliated. The Cedar Lake Pluton has weak to moderate fabric developed at its margin and a weak foliation in its interior.

The variable orientation of the strong fabric within the greenstone belt results, in part, from post-fabric folding. At Mussy Lake the granite-greenstone boundary and strong fabric are subparallel and folded. A well-developed crenulation cleavage deforms the earlier margin-parallel strong fabric and is axial planar to the fold axial trace. Similarly, the Heron Bay Pluton is interpreted as folded along with an earlier-formed strong fabric in the greenstone belt. Again, this folding is associated with a crenulation cleavage in the greenstone belt rocks. The Gowan Lake Pluton roughly follows the contact between the granite-greenstone belt which is concave to the northeast. It is unclear if the pluton configuration resulted from emplacement into an already curved boundary of the greenstone belt, or from subsequent folding. Observations by G.P. Beakhouse (OGS) of magmatic flow foliations in the pluton that parallel the granite-greenstone boundary support the interpretation of post-folding emplacement.

Metamorphic grade increases both from west to east and as one approaches external and internal granitoid bodies. In metabasites, the increase in metamorphic grade is reflected by a decrease in chlorite content with an increase in hornblende content, the appearance of garnet and/or cummingtonite and, at the highest grades, the appearance of clinopyroxene. In metapelites, mineral assemblages progress from west to east from garnet-chlorite to staurolite to garnet-biotite-sillimanite assemblages. Calcareous assemblages exhibit a transition from quartz-iron carbonate+/-chlorite in the west to quartz-calcite-amphibole assemblages to epidote-garnet+/-clinopyroxene, hornblende assemblages in the east.

In general, the strong fabric in the greenstone belt is defined by peak metamorphic mineral assemblages. This fabric is deformed by the later crenulation cleavage that is associated with folding of internal plutons and the granite-greenstone boundary. The general westward component of plunge to

linear elements and increase in metamorphic grade from west to east suggests that deeper erosional levels of the greenstone belt are exposed in the east. At present a general two-stage deformation model is envisaged for the greenstone belt. An early, high-temperature, high-strain stage generated the well-defined foliation that is parallel to unit contacts and the granite-greenstone boundary. There appears to be a paucity of map-scale folds related to this deformation; however, T.L. Muir (OGS) has observed folds with strong axial planar fabric near the Hemlo gold deposit. A low-temperature, regional, compressive deformation stage followed and resulted in folding of: the earlier-formed, high-strain fabric; internal plutons; and, the granite-greenstone boundary. This later deformation stage, which may consist of more than one generation of folding and faulting, is interpreted to be the main contributor to the current geometry of the granite-greenstone belt.

Published geochronology allows a general time frame to be assigned to the deformation stages. The early high-temperature deformation occurred between 2.695 Ga (age of metavolcanic rocks involved in the deformation) and 2.688 Ga (age of Heron Bay and Cedar Lake plutons). The younger low-temperature deformation occurred between 2.688 Ga (age of Heron Bay Pluton) and, speculatively, 2.678 Ga (age of Gowan Lake Pluton). At a subprovince scale the general history of the Hemlo greenstone belt is similar to the Manitouwadge greenstone belt. Although conjectural, the high grade metamorphism and early deformation may be correlative with comparable "D2" events (Zaleski et al. 1995) recorded in the Manitouwadge greenstone belt. The late folding may correlate with formation of the "D3" (Zaleski et al. 1995) Manitouwadge synform.

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Structural and Metamorphic constraints on the tectonic history of the Southern Province in the Sault Ste. Marie - Espanola area.

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Southern Province rocks exhibit a beguilingly simple concave to the north structural grain. Regional structures are commonly attributed to compression during Penokean Orogeny; however, structural, intrusive, and metamorphic relationships permit other interpretations. North of the Murray Fault rocks of low metamorphic grade are deformed about generally upright folds and reverse/thrust faults. The folds affect 2.22 Ga Nipissing Gabbro and the 1.85 Ga Sudbury complex and are commonly associated with weakly to moderately developed, steeply dipping, axial planar cleavage. Confusion about the age of folding arises because many gabbro dykes occupy structures parallel to the axial trace of some regional folds which may indicate deformation prior to, or synchronous with, gabbro emplacement. Scenarios that account for observed relationships include: 1) gabbro dykes and sills that were emplaced into structurally prepared sites (fold hinges and axial planar faults/fractures); 2) crustal flexure resulting in fracturing and faulting of the basement and cover accompanied or followed by emplacement of gabbro dykes and sills (subsequent compression resulted in folding); and 3) two or more mafic intrusive events may be confused as a single event (one represented by pre-folding 2.22 Ga gabbro sills and one by post-folding gabbro dykes).

South of the Murray Fault there is evidence for at least 3 deformational events including: 1) pre-Nipissing faulting and large-scale folding related to syn-depositional and/or post-depositional unconsolidated deformation of strata; 2) "D1" layer-parallel structural elements reflecting high extensional strain that formed pre to syn peak metamorphism; and 3) "D2" regional folds and faults parallel structures north of the Murray fault that deform metamorphic isograds and are associated with a crenulation cleavage. Both D1 and D2 structures south of the Murray Fault affect Nipissing gabbro; however, field observations indicate that D2 structures post-date the 1.75 Ga Cutler Batholith.

The origin of high-grade metamorphic assemblages involving staurolite and biotite in the McKim Formation south of the Murray Fault is a perplexing aspect of Southern Province tectonics. High grade metamorphism was previously attributed to crustal thickening during the Penokean Orogeny. Although this could explain the mesoscopic D1 structural elements oriented at a low angle to bedding, the lack of regional structural evidence for the required thickening during D1 and the observation that metamorphism predates regional folding do not support this interpretation. Furthermore, geobarometry indicates relatively low-pressure (2-3 kbar; 6-10 km) metamorphism at a crustal thickness close to, or less than, the estimated thickness of the Huronian clastic prism which would also seem to preclude metamorphism related to crustal thickening. Crustal extension and increased mantle heat flow might better explain the near layer-parallel foliation, lack of structural evidence for significant crustal thickening, and the low-pressure metamorphism.

In general, extension of the Superior craton and deposition of the Huronian Supergroup is thought to have occurred between 2.45 Ga and 2.22 Ga, the age of lower Huronian volcanic rocks and Nipissing gabbro, respectively. However, there is a well-established angular unconformity between the 2.45 Ga volcanic rocks and overlying formations and no volcanic units are reported from within strata above the unconformity. Consequently, crustal extension and resultant deposition of units above this unconformity may have shortly preceded 2.22 Ga Nipissing mafic magmatism. Deep parts of the basin may have been subjected to elevated heat flow during extension resulting in D1 structural elements and high-temperature, low-pressure metamorphism inferred to shortly follow Nipissing magmatism. Post metamorphic regional compression at ~1.75 Ga generated the regional folds and associated axial planar cleavage / crenulation cleavage. The above interpretation invokes substantial pre- and post-Penokean tectonic events, but does not require deformation or metamorphic events in the 1.85-1.82 Ga interval.

The Early Proterozoic break-up of the Superior Craton: Implications of drill core and geophysical data south of the Gogebic range, northern Wisconsin.

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Exploration drill cores and geophysical data reveal several nearly continuous belts of Early Proterozoic metasedimentary and metavolcanic rocks that extend northeasterly from Butternut, Wisconsin to the south end of Lake Gogebic, Michigan. The belts, shown by Sims (1992) as Blair Creek Formation and as undifferentiated Chocolay and Menominee Group rocks, are separated by expanses of gneissic granitoid rocks. The distinct geophysical boundaries on the belts suggests that they are fault bounded. The aeromagnetic and electromagnetic geophysical data provide information on the nature and distribution of rock units encountered in the drill cores.

Some cores contain intercepts of up to 100 meters of dolomitic marble, some of which contains interbedded biotite schist. Other cores contain granular and laminated iron-formation that grades abruptly downward into massive quartzite, which, in turn, grades into more thinly bedded quartzite and then into interbedded quartzite and biotite schist. Iron-formation is commonly interbedded with basaltic pillow lavas, pillow breccias and hyaloclastite units. Some cores contain granular jasper and hematite iron-formation interbedded with basaltic rocks. Several cores intersected zones of strongly foliated granitoid gneiss. Some of the cores contain breccias composed of tabular clasts of iron-formation, quartzite, dolomite, or mixtures of these lithologies in a matrix of graphitic biotite schist. Several of these breccia zones may be present in a given core.

Lithologies encountered in the cores are similar to rock units exposed to the northeast in the eastern Gogebic range in Michigan (LaBerge and Klasner, 1994). The granitoid gneiss may be slivers of Archean basement, similar to the Presque Isle granite exposed near Marenisco, Michigan. The dolomite is comparable to the Bad River Dolomite exposed east of Wakefield, Michigan. The quartzite is similar in all respects to the Palms Formation exposed throughout much of the length of the Gogebic range. The iron-formation with interbedded volcanic rocks is very similar to the Ironwood Iron-Formation and interbedded Emperor Volcanic Complex north of Marenisco, Michigan. The geophysical data indicate a near-continuity of units within these belts and the eastern Gogebic range. Therefore, it appears likely that the units are correlative from the Gogebic southward as suggested by Allen and Barrett (1915) and Dutton (1983).

The volcanic rocks are largely restricted to units containing iron-formation, consistent with stratigraphic relations on the eastern and western ends of the Gogebic range, (LaBerge and others, 1995). This study also supports the observations of Allen and Barrett (1915, p.90-91) that volcanic rocks interbedded with iron-formation are widely distributed in several belts of rocks south of the Gogebic range. Thus, volcanism contemporaneous with iron-formation deposition is present on the eastern and western ends of the Gogebic range and with iron-formation units along the length of the range to the south. The widespread occurrence of volcanic rocks south of the Gogebic range indicates a broad distribution of volcanism southward toward the proposed margin of the Superior Craton.

The breccia units are interpreted as depositional breccias, where shallow-water sediments (dolomite, quartzite, and iron-formation) slumped into deeper, stagnant basins in which carbonaceous, pyritic mud was accumulating. These stagnant basins are interpreted to be restricted, fault-bounded basins into which periodic slumping of shallow-water sediments occurred along fault scarps.

Collectively, the data suggest that 1) a platformal environment at least 60-100 km wide extended southward from the present Gogebic range, on which dolomite and quartzite of the Marquette Gange Supergroup accumulated; 2) volcanism commenced during iron-formation deposition, probably associated with rifting and the formation of fault-bounded stagnant basins. Volcanism may have contributed iron and silica to the overlying ocean water, which was then precipitated as iron-formation; 3) breccias containing clasts of shallow-water sediments within carbonaceous sediments suggests that rifting and the formation of stagnant basins occurred along the margin of the Superior Craton. In this interpretation the Gogebic range and the rocks in the several "ranges" to the south are pre-collision, and not related to foreland basin evolution. Available evidence indicates that the Tyler and Coppers Formations unconformably overlie the iron-formation. These formations are interpreted to be foreland basin deposits related to collisional tectonics, and to be significantly younger than the iron-formation.

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**Mineral Potential Study of a Greenstone Belt
Using Boulder Tracing, Ely-Bigfork Area, Minnesota**

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Abstract

The Ely-Bigfork area of northern Minnesota is an area of complex Archean bedrock geology. Bedrock lithologies, structure, alteration, mineral occurrences and exploration geochemistry indicate there should be undiscovered valuable metallic mineral deposits. The poster displays sample site locations and anomalous results which indicate gold or base metal potential. The granite - greenstone belt (Morey, 1996) is similar to those hosting economic mineral deposits in the Archean of Canada and Scandinavia.

The objective of this project is to provide a reconnaissance study of mineral potential for a sixty-one township area in northern St. Louis County, southeastern Koochiching County and northeastern Itasca County. This is achieved by mapping alteration and analysis of mineralized rock samples found in glacial drift deposits from 144 sites, mostly gravel pits. Anomalous gold values ranged to 3,598 ppb, with arsenic values up to 1,900 ppm. Base metal values include zinc to 2,899 ppm, copper to 14,944 ppm and lead to 248 ppm, also barium to 1,980 ppm. Partial analytical results are presented in a table with anomalous areas designated as Mineral Potential Areas (MPAs). The map presents site number, designation as gold or volcanogenic massive sulfide model, and MPA number. Samples of analyzed rock are displayed for many sites. The table Mineral Potential Areas From Analysis displays selected analysis used to model mineral potential.

The location of the source of mineralized samples is indicated by:
1. Development of mineralized-altered boulder dispersal trains. 2. The amount of mineralized rock at the sample site which decreases with distal dispersion and denudation. 3. Hand lens classification of lithologies contributing pebbles to a randomly selected sample of 100 pebbles from each site which are compared with mapped bedrock lithology (Morey 1996). MPAs 1, 2, 7, 8 and 17 are in an area mapped by Mooers, et al. (1996) as scoured bedrock uplands or Rainy Lobe deposits. By all the criteria the northern sites of MPA 1 and 2, and all of MPAs 7 and 17 are near the bedrock source of mineralized rock. West of these MPAs, Mooers, et al. map additional dispersion by the Koochiching Lobe. MPAs 3, 4, 5, 9, 10, 11, 12, 13, 14 and 15 are reasonably close to their source by most of the criteria. MPA 6, 8 and 16 might be some distance from their source.

Morey, G.B., Compiler, 1996, Geologic Map of Minnesota, Minnesota Geological Survey, Digital Version

Mooers, H.D., et al., 1996, Geomorphology of the Basswood Lake, Crane Lake, Little Fork, Ely, Vermilion Lake and Bigfork 1:1,000,000 quadrangles and the development of the Land Type Association layer of the Ecological Classification System, Minnesota Department of Natural Resources - Division of Forestry

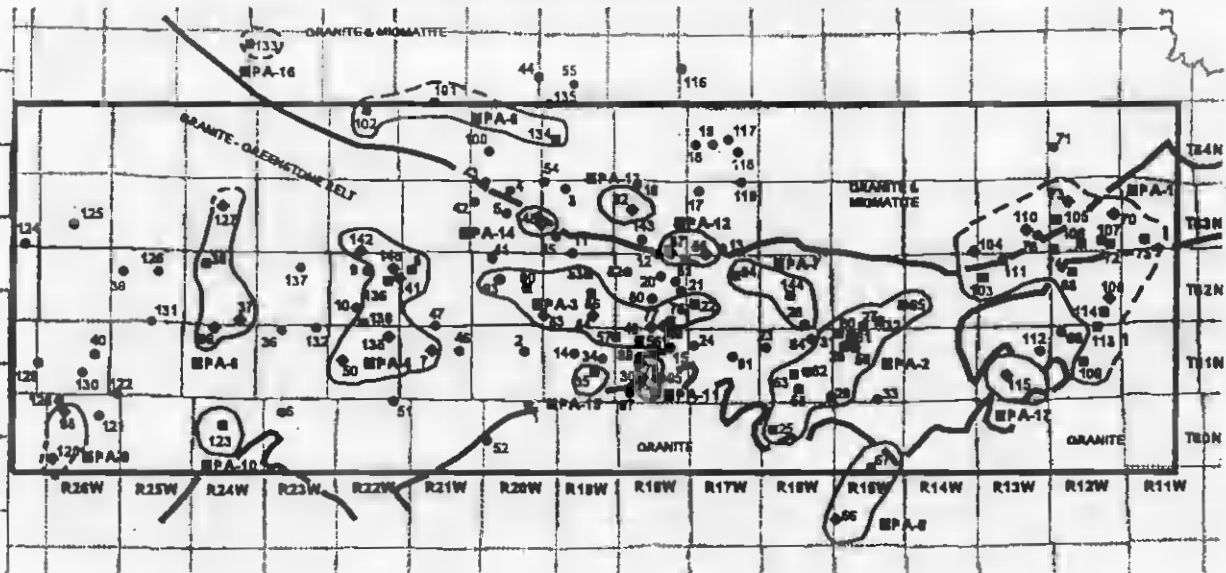


MINERAL POTENTIAL AREAS

-  P318 STUDY AREA
-  VMS BASE METAL
-  MINERAL POTENTIAL AREA
-  GOLD



• SITES WITH NO MINERAL POTENTIAL



SCALE 1:1,000,000

THE PETROLOGY OF GREENSPAR:
A PROTEROZOIC PORPHYRITIC DIABASE DIKE;
PIFHER AND IRWIN TOWNSHIPS, LAKE NIPIGON DISTRICT, ONTARIO
by Frank R. Luther, Geology, UW-Whitewater, Whitewater, WI 53190

This approximately 50 m wide porphyritic diabase dike, outcropping in western Irwin and Pifher Townships in the Lake Nipigon district, is locally known as greenspar. The dike has a characteristic greenish mottled appearance in outcrop as a result of sausseritized plagioclase glomerophenocrysts in a diabase groundmass. The dike strikes due north and dips vertically. It is located approximately 15 km east of Lake Nipigon and 5-20 km north of Hwy 11.

Mackasey (1975) mapped the dike as segments off-set by east-west faulting and suggests that only one dike was originally intruded. Kresz and Zayachivsky (1989) observed chill borders on dike apophyses and stated that the dike has been seen some 50 km south of Irwin Township. Both reports stated that the glomerophenocrysts are erratic in distribution; Mackasey reported a segregation of the glomerophenocrysts into bands at one location. Alteration of the country rock was not reported by these workers nor was it seen by the author.

The greenspar dike is of Proterozoic age. Mackasey (1975) determined that this dike is cut by the large middle or late Proterozoic (Keweenawan?) sill in Irwin Township. There are no radiometric dates on this rock or associated rocks.

A whole rock chemical analysis of the greenspar is presented in Table 1. The texture and mineralogy of this rock were studied by petrographic and electron microprobe analysis. The rock consists of

- 20% glomerophenocryst plagioclase: euhedral, 1-5 cm, with remnant plagioclase cores (an_{83}), the bulk of these crystals are altered to a very fine-grained mixture of albite, epidote, sericite, and zeolite(?).
- 45% groundmass plagioclase: normally zoned core (an_{66}) to rim (an_{61}), subhedral laths, 0.1-0.3 x 0.5-1.0 mm, cores are rarely altered to a fine-grained mixture of sericite and epidote.
- 30% augite: zoned core Mg_{70} to rim Mg_{40} , interstitial to subhedral, 0.2-0.3 mm.
- 4% opaques: euhedral magnetite, ilmenite, and pyrite, 0.1-0.3 mm.
- <1% quartz: interstitial grains 0.1-0.3 mm.

The glomerophenocrysts have remnant cores of an_{83} composition while the bulk of these large crystals are altered to a mixture of albite, epidote, sericite, and zeolite(?). The glomerophenocrysts are interpreted as phenocrysts because of their euhedral form. No broken crystals, xenocrysts of other composition or mineralogy, or xenoliths were observed. The glomerophenocrysts, being highly calcic, were easily sausseritized during sub-solidus events. The normally-zoned plagioclase of the groundmass with an average composition of an_{60} was not as susceptible to alteration; some crystals show minor alteration of the more calcic cores. Clinopyroxene in the

groundmass is zoned from Mg₇₀ in the core to Mg₄₀ in the rims; there is minor alteration of the clinopyroxene to actinolite and zeolite(?). Euhedral Mn-bearing ilmenite (sometimes skeletal or intergrown with Ti hematite?), magnetite, and pyrite are present throughout the groundmass. Olivine was not observed.

It is interesting to speculate on the age and origin of the greenspar. The length of 15 (perhaps up to 65) km, minimal variation in width, vertical dip, uniform strike, and apparent over-all compositional homogeneity point to a deep-seated source and a long period of cooling at considerable depth to crystallize the exceptionally large glomerophenocrysts. Following this period of quiescence, the magma was intruded into cooler Archean country rocks where the remaining melt cooled rapidly enough to form zoned plagioclase and clinopyroxene. The glomerophenocrysts were deuterically altered soon after emplacement while the groundmass plagioclase, less calcic in composition, and other groundmass minerals were less affected. With respect to the time of intrusion, the mineralogical similarity to middle or late Proterozoic (Keweenaw?) diabases is (weak) evidence that this rock may be an early phase of Keweenaw activity. Logically, a lone dike in this location, given the characteristics enumerated above, with no compositional similarity to lamprophyre or kimberlite, could easily be an early phase of Keweenaw magmatic activity. Alternatively, the east-west strike-slip offsets noted by Mackasey are not consistent with mostly dip-slip Keweenaw faults resulting from rifting. This faulting could indicate a pre-Keweenaw origin of the greenspar.

Table 1. A bulk chemical analysis of the greenspar. (XRAL Laboratories)

SiO ₂	48.9	Rb	2 ppm
Al ₂ O ₃	13.2	Sr	209 "
CaO	11.0	Y	22 "
MgO	6.02	Zr	105 "
Na ₂ O	1.94	Nb	11 "
K ₂ O	0.28	Ba	137 "
FeO _t	14.2		
MnO	0.21		
TiO ₂	1.33		
P ₂ O ₅	0.15		
Cr ₂ O ₃	<.01		
LOI	<u>0.85</u>		
TOTAL	98.1		

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Initial results of Ar/Ar mineral dating from the Peavy node area of northern Michigan and Dunbar dome area of northeastern Wisconsin.

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The origin of gneiss domes and metamorphic nodes exposed within the Penokean orogenic belt has perhaps been one of the most important and controversial areas of geologic research in the Lake Superior region. Although the nodal isograd patterns appear grossly similar in map view, they may actually have very different origins, may have formed at different times, and may even be the product of polyphase metamorphism. For instance, Emilio et al. (1996) on the basis of textural relationships suggested that the Peavy metamorphic node in northern Michigan may be the result of three discrete metamorphic events. In addition initial Ar/Ar thermochronologic results within the Peavy node (Winnet, 1981) are suggestive of several post-orogenic reheating episodes. Finally, numerous Rb/Sr and K/Ar mica dates from within and outside (mainly south) of the Peavy node also suggest a protracted history of post-orogenic uplift and/or reheating (Aldrich et al., 1965; Peterman et al., 1985). We report here the results of new Ar/Ar mineral dates which further elucidates the thermal history of this area.

Result of hornblende dating. We dated one hornblende separate (96-MI-4) from an amphibolite schist collected from the south side of the Felch Trough (~7 km west of Foster City, MI). This sample yielded an excellent plateau date of 1799 ± 6 Ma (and concordant total gas date of 1797 Ma). This date is comparable to the oldest post-Penokean K/Ar hornblende date from this area obtained by Aldrich et al. (1965) and is interpreted to represent the time of initial cooling below ~500°C after Penokean-age regional metamorphism. We note that previous hornblende Ar/Ar total gas dates and K/Ar dates obtained to the west are substantially younger (predominantly 1730-1500 Ma) and may well represent localized thermal overprinting effects possibly associated with the long recognized 1630 Ma metamorphic event or even intrusion of the Middle Proterozoic Wolf River Batholith.

Result of muscovite dating. Muscovite from an Archean muscovite-biotite schist collected at Foster City (94-MI-1) showed some possible recoil effects but yielded a plateau date of 1673 ± 6 Ma over the last 50% of the gas released. Coarse muscovite from a pegmatite (96-MI-5) located in the north central part of the Felch Trough gave an excellent plateau date of 1653 ± 4 Ma. These dates are the oldest mica dates obtained from the area by either the Ar/Ar or K/Ar methods (see Aldrich et al., 1965 and Winnet, 1981). They are roughly comparable to the 1610-1680 Ma Rb/Sr and Ar/Ar biotite dates obtained from the Republic area to the north (Van Schmus and Woolsey, 1975; Schneider et al., 1996) and may indicate the time of initial slow regional cooling through mica closure temperatures (~350-300°C) long after the Penokean Orogeny. Alternatively, these dates may represent nearly complete thermal resetting associated with the 1630 Ma low-grade event although the morphology of the spectra do not seem to support this interpretation.

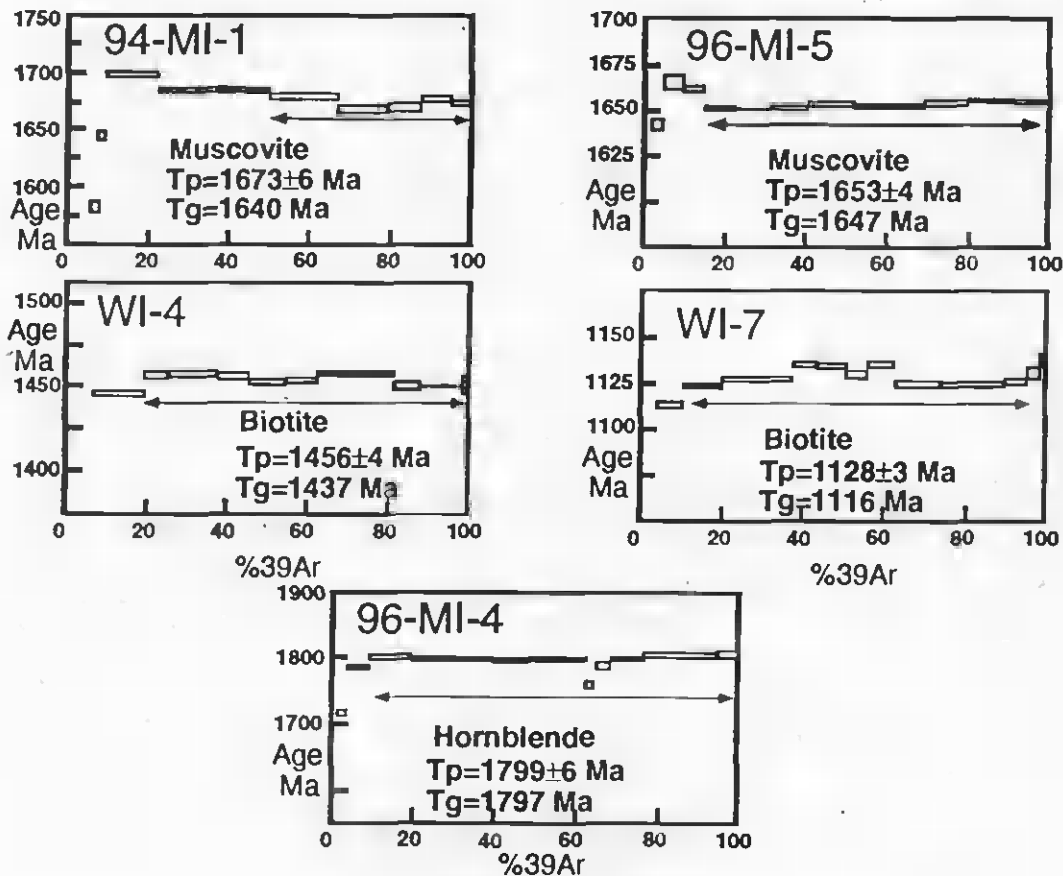
Result of biotite dating. We dated two biotite separates from rock samples collected in northeast Wisconsin south of the Niagara Fault. A sample of a Penokean pluton collected near Amberg, WI (southeast of the Dunbar dome) yielded a plateau age of 1456 ± 4 Ma. Rb/Sr biotite dates from this locality and from several surrounding localities are substantially younger (1350-1390 Ma, Peterman et al., 1985). The Ar/Ar biotite date is nearly concordant with the intrusion age of the Wolf River batholith (exposed ~25 km to the southwest). The nearest exposed portions of the batholith contain miarolitic cavities and a late differentiate of it (the Belongia Granite) has a composition which suggests emplacement at shallow crustal levels (<4 km, Anderson and Cullers, 1978). Considering that the batholith extends for a considerable subsurface distance beyond its map view exposure (Allen and Hinze, 1992), we suggest that the 1456 Ma biotite date represents thermal resetting of shallow crustal rocks intruded by the Wolf River Batholith.

Biotite from a biotite augen gneiss (WI-7) collected within the Dunbar dome (~8 km north of Dunbar, WI) yielded a near-plateau date of 1128 ± 3 Ma (and total gas date of 1116 Ma). This date is nearly concordant with previous Rb/Sr biotite dates obtained from this locality (Peterman et al., 1985) and

from localities to the west (i.e., the locus of <1.2 Ga Rb/Sr biotite dates called the Goodman Swell by Peterman and Sims, 1988). Our date is consistent with the interpretation that this area cooled during uplift related to loading along the Keweenaw rift but may also alternatively be explained, perhaps, by resetting due to subsurface Keweenaw igneous activity.

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THE SUB-BARABOO PALEOSOL, WISCONSIN: GEOCHEMICAL EVIDENCE FOR PROTEROZOIC WEATHERING AND METASOMATISM

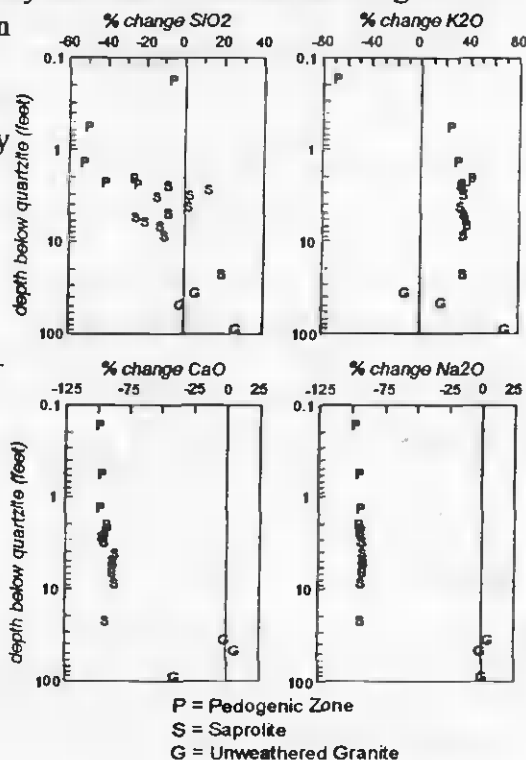
MEDARIS, L.G., Jr., BAUMGARTNER, L.P. and DOTT, R.H., Jr., Dept. of Geology & Geophysics; McSWEENEY, K., Soil Science; all at University of Wisconsin-Madison, Madison, WI, 53706

Precambrian paleosols provide important data for the interpretation of paleoclimates and paleoatmospheres, but the chemical compositions of such ancient soils have commonly been modified by subsequent diagenesis or metamorphism. A paleosol has recently been discovered at the base of the post-1760 Ma Baraboo Quartzite on Baxter Hollow Granite (Medaris et al., 1996a, 1996b), and chemical analyses have been obtained to evaluate the conditions of weathering and possible effects of metasomatism. The geochemical profile of the sub-Baraboo paleosol is consistent with weathering under conditions of intense leaching, but appreciable potassium was added to saprolite and the associated pedogenic zone during later metamorphism.

Description of the sub-Baraboo paleosol: the quartzite-granite contact in Baxter Hollow is not exposed in outcrop, but the contact was penetrated by eight holes that were drilled by the U.S. Army Corps of Engineers in 1959. Material from the contact zone was recovered only in drill core from Hole No. 613, in which overlying pebbly quartzite is separated from underlying granitic saprolite by a 2.5 foot-thick, reddish-purple pedogenic zone, consisting of fine-grained hematite, quartz, and illite (+kaolinite). The pedogenic zone shows features that are commonly associated with physical reorganization (e.g., repeated wetting and drying) of weathered rock in soil-forming environments, which include: 1) aggregates of clay-size and larger grains with small intra-aggregate voids, 2) a network of large interconnected vertical, horizontal and oblique voids separating the aggregates, 3) discrete accumulations of clay- and silt-size materials along some void walls and large grain edges, and 4) stress orientation within some clay-size accumulations.

Granitic texture is preserved in saprolite, but biotite is largely replaced by hematite, and feldspar is completely replaced by illite; the first feldspar in granite is located ~30 feet below the quartzite. We presume that the intensity and frequency of processes driving physical reorganization of the soil-saprolite profile diminished with increasing depth below the land surface.

Geochemistry: XRF analyses have been obtained for major and selected trace elements in twenty samples. Data for four oxides are plotted in the adjacent figure in terms of % change with respect to the average of two unweathered granite samples closest to saprolite, and normalized to Al_2O_3 , which is assumed to be immobile during weathering. Some features of the paleosol chemical profile resemble those of modern soils which are produced by intense chemical leaching, such as a decrease in SiO_2 and severe depletion in CaO and Na_2O , due to solution of quartz and release of Ca and Na from



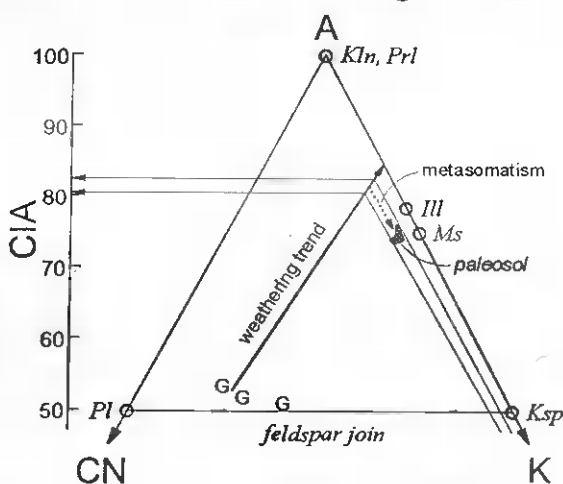
plagioclase during replacement by kaolinite. However, Ca and Na depletion should be accompanied by K depletion due to weathering of K feldspar, but with the exception of the uppermost sample, K₂O is 30-40% higher in the paleosol, compared to average granite. We believe that all feldspar in the paleosol was altered during weathering and that K leaching occurred, but that K was reintroduced during later metamorphism by fluid flow along the sub-Baraboo unconformity. Note that detrital feldspar is rare in quartzite, and interlayered, highly aluminous metapelites, consisting of pyrophyllite+kaolinite+quartz, are impoverished in K, Na, and Ca. Similar chemical features have been described from sub-Huronian paleosols on granite at Pronto, Ontario (Gay & Grandstaff, 1980), and Ville Marie, Quebec (Rainbird et al., 1990), and interpreted as the result of K-metasomatism during diagenesis or low-grade metamorphism of pre-existing weathering profiles.

The relative effects of weathering and metasomatism on paleosols can be evaluated by using a plot of molar Al₂O₃ (A), CaO+Na₂O (CN), and K₂O (K). A theoretical weathering trend for Baxter Hollow Granite was calculated from the CIPW norm of average granite and release rate constants for feldspars (Nesbitt & Young, 1984). The relative positions of the weathering trend and analyses of sub-Baraboo paleosol indicate an addition of ~10 mol% K₂O during metasomatism, which is comparable to the ~14 mol% estimated for the Ville Marie paleosol (Fedo et al., 1995). The chemical index of alteration (CIA), which is defined as $Al_2O_3 / (Al_2O_3 + CaO + Na_2O + K_2O)$, can be determined for pre-metasomatized paleosol by extending lines from the K₂O apex through the paleosol analyses, to intersect the weathering trend, yielding values of 81-83. Such values are significantly higher than those obtained, if the effects of K-metasomatism are neglected.

Conclusions: a well-developed weathering profile was established on the Baxter Hollow Granite prior to deposition of the Baraboo Quartzite. During later metamorphism and folding of the quartzite, significant amounts of K were added to the paleosol by fluids channeled along the sub-Baraboo unconformity. An investigation of fluid inclusions is underway to determine the characteristics of the metasomatizing fluids. The time of weathering remains unknown, other than being younger than 1760 Ma. An apparent Rb-Sr isochron age of the paleosol is 1360±50 Ma, raising the intriguing possibility that K-metasomatism, metamorphism, and folding might have been related to Wolf River events (~1400-1500 Ma).

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RESULTS OF MODERN ALLUVIUM SAMPLING FOR KIMBERLITE INDICATOR MINERALS, WAWA-KINNIWABI LAKE REGION, AND THE IMPLICATION FOR KIMBERLITE EXPLORATION, NORTHEASTERN ONTARIO.

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Quaternary mapping and till sampling over the Michipicoten greenstone belt, north and northeast of Wawa, were initiated in 1990 and completed in 1991. Following the discovery of diamonds in modern alluvium by a prospector in 1993, the Ontario Geological Survey conducted a modern alluvium sampling program in 1994. The area sampled included the region originally mapped in 1990 and 1991. At the same time, Quaternary mapping, modern alluvium sampling and till sampling were completed in the Michipicoten River valley, south of Wawa.

Following the release of data in 1994, a small diamond related staking rush occurred. The distribution of kimberlite indicator minerals suggested a relationship to a northeast structural trend. As modern alluvium was collected over only a part of this structure during the 1994 survey, the Ontario Geological Survey initiated a second modern alluvium and till sampling program in the Kinniwabi Lake area, east of Wawa, in 1996.

Kimberlite indicator minerals recovered include: 1) chrome pyrope garnets; 2) chromite; 3) magnesium-rich ilmenites and chrome diopsides. To date, a total of 7 "G10" chrome pyrope garnets, 60 "G9" chrome pyrope garnets, 3 high chrome chromites, 217 low chrome chromites, 292 magnesium-rich ilmenites and 318 chrome diopsides have been recovered. The distribution and relative concentration of these heavy minerals clearly illustrates a correlation with northeast-trending regional faults associated with the Kapuskasing Structural Zone. In particular, a number of sample sites along the fault controlled Shikwamkwa River valley and the Shikwamkwa Lake basin yielded significant numbers and types of kimberlite indicator minerals. These minerals are similar to recovered in the Trout Creek drainage system, located along strike to the southwest, and at Dalton, situated along strike to the northeast. This may suggest that faults within the Kapuskasing Structural Zone, from Wawa to the James Bay Lowland, could represent promising kimberlite exploration targets.

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THE HEMLO GOLD DEPOSIT: IT MAY BE GOLD BUT IT'S NOT BLACK AND WHITE

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Over 15 years have passed since the "discovery" of the Hemlo gold deposit. A plethora of ideas as to its origin has emerged. The diversity of interpretations, all drawing upon some type of hydrothermal alteration system, reflects the complex geological history of the area, including the deposit. The implications for observations and interpretations regarding the deposit must be integrated with an overall assessment of events. The establishment of fundamental relationships among geological events is paramount to developing an appropriate depositional model and ultimately a reliable exploration strategy.

The deposit currently lies within one of several high strain zones, largely at or near the hanging-wall side of the south limb of a 2.5 km amplitude, S-shaped, F_2 fold. The ore overall transgresses units. In the western part of the deposit, ore occurs largely as several east-striking, low-grade zones within massive (subvolcanic) and fragmental, felsic, quartz-plagioclase-phyric rocks. In the central and eastern parts it occurs mostly as 1 to 2 large, tabular, east-southeast-striking, higher grade zones within highly feldspathized rocks.

The fundamental relationships from this work are that mineralization and alteration: 1) currently are largely structurally controlled; 2) post-date regional-scale (D_2) folding; 3) predate felsic to intermediate intrusions (plutons and dikes); 4) predate, or are synchronous with, the development of D_2 high-strain zones; 5) predate regional scale D_3 ductile and brittle-ductile flattening, which resulted in superposed dextral shear constrained to zones of existing high strain and/or fissile rocks; and 6) predate regional metamorphism. By inference, the mesoscopic and microscopic features which we presently observe represent modified primary features and the current setting of the deposit does not accurately reflect the original deposit characteristics. The role of superposed alteration and remobilization of deposit-related metals is considered to have been generally underrated. The rearrangement of primary characteristics impedes a simple reconstruction of the mineralization/alteration events.

Syngenetic and skarn models do not account sufficiently for the observed field relationships. However, simple porphyry and shear-zone-hosted models, as presented, have notable shortcomings. Problems revolve around the relationship of the deposit to the origin of the quartz-plagioclase-phyric rocks, the identification of superposed alteration/mineralization events, the initial role of structural control and the present distribution of various mineral phases (e.g., muscovite, microcline). Most of the ambiguity arises from enigmatic relationships resulting from the complex history of superposed events. Nevertheless, the Hemlo deposit does not appear to fit a single classic deposit model. Rather it may be linked to fluids, from an unexposed porphyry(?) magma, which were channeled by existing structural weaknesses during active tectonism.

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PETROGENESIS OF CHENGWATANA VOLCANICS, MINNESOTA AND WISCONSIN

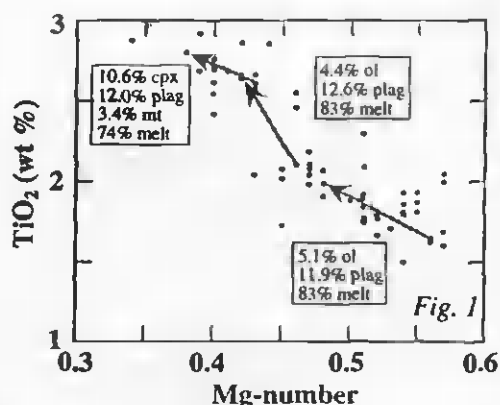
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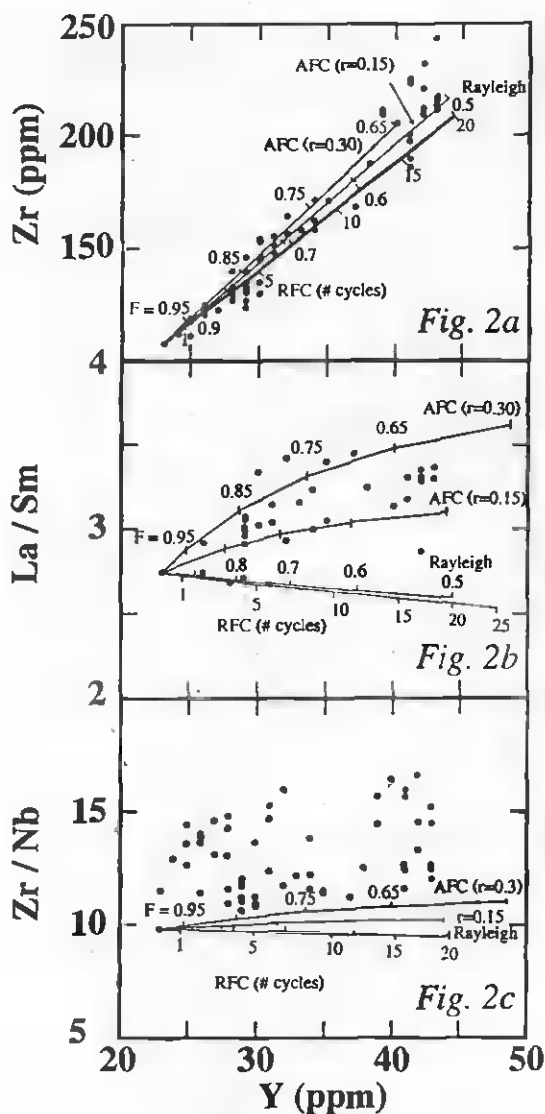
The Chengwatana Volcanics (CV), a >3000 meter unit of high iron and aluminum tholeiitic basalt with interflow sediments, were erupted south of the presumed Penokean suture zone (the site of 2.0 Ga southward dipping subduction) and are the southernmost exposed lavas of the 1.1 Ga Midcontinent rift (MCR), making them ideal for studying magmatic processes along the rift axis. CV flows contain primary plagioclase (~60% modal An_{60}), clinopyroxene (~30% modal $Wo_{35}En_{45}Fs_{20}$), and Fe-Ti oxides (~8% modal). The geochemistry of the CV is similar to basalts from other eruptive centers along the MCR; the flows are characterized by low magnesium ($Mg\# = 0.58-0.37$), and can be divided into high- and low- TiO_2 groups, resembling the Portage Lake Volcanics (PLV). The CV are enriched in incompatible trace elements (ITE) similar to PLV basalts as well as basalts from the Powder Mill Group (PMG), and group 6 flows of the Mamainse Point Formation (MPF), but exhibit more pronounced Nb and Ta anomalies. ITE are negatively correlated with $Mg\#$ and are positively correlated with TiO_2 . Isotopic compositions (ϵ_{Nd} from +0.1 to -4.5) are positively correlated with the Nb anomalies and are negatively correlated with ITE abundances and ratios (e.g., Y, La/Sm), TiO_2 , and indices of fractional crystallization (e.g., $Mg\#$). Petrographic observations coupled with geochemical trends suggest that the CV were derived from an enriched mantle source, similar to some other MCR rocks, and assimilated continental crust while fractional crystallization occurred in crustal magma chambers.

Geochemical modeling provides constraints on the petrogenetic processes involved in CV genesis and evolution. Mass-balance models¹ demonstrate that the major element trends exhibited by the CV flows can be accounted for by 5-50% crystallization of varying proportions of olivine (0-6%), plagioclase (5-20%), clinopyroxene (0-15%), magnetite (0-5%), and ilmenite (0-5%). Although no olivine is observed in thin section, geophysical studies of the MCR² suggest the presence of high-velocity layers in the lower crust which might be mafic cumulates. Representative models are illustrated in Figure 1.

Closed- (Rayleigh) and open-system (RFC)³ fractional crystallization models (using mineral proportions predicted by the mass-balance equations and from petrographic analysis) successfully model the enrichment of some trace elements (e.g., Zr, Hf, Y; Fig. 2a), but fail to model highly incompatible trace elements and ratios (e.g., La/Sm, Zr/Nb; Fig. 2b,c).

Models of combined fractional crystallization and assimilation have been used to account for the geochemical variation in basalts from various parts of the MCR. Simple mixing models between CV and average Archean granulite do not accurately predict trace element compositions of CV flows, but Nd isotopic compositions constrain the amount of crustal component in the CV to <30%. Combined assimilation and fractional crystallization (AFC) models⁴ with 15% and 30% crustal assimilation of a variety of crustal compositions





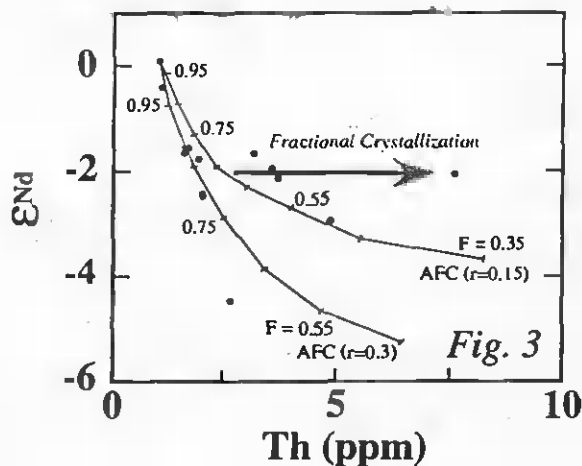
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(lower, upper, and bulk crust; granulite; shale) successfully predict ϵ_{Nd} and most trace element abundances of enriched CV flows (Fig. 2a,b). AFC models do not predict the low Nb (high Zr/Nb, Fig. 2c).

The low Nb concentrations can be explained by (1) assimilation of a crustal components with extremely low concentrations of Nb relative to ITE, (2) melts derived from lithospheric mantle that was variably depleted in Nb relative to other ITE, or (3) melts derived from asthenospheric mantle which had incompatible elements, but little Nb, added during chemical interaction with lithospheric mantle.⁵ Lithospheric mantle could have become enriched in incompatible elements (relative to Nb) by metasomatism related to Penokean subduction. An enriched mantle/lithospheric mantle source for MCR rocks has been proposed for volcanics from the early stages of rifting, including flows from the MPF and the PMG.^{6,7,8} A modified lithospheric mantle source has also been proposed for the Portage Lake Volcanics.^{9,10}

Geochemical models indicate that a variety of petrogenetic processes, including derivation from multiple mantle sources, crustal assimilation, and fractional crystallization, operated to produce the trace element and isotopic variations exhibited by the CV.



CORRELATIVE SEQUENCES WITHIN THE MARQUETTE RANGE SUPERGROUP (MICHIGAN) AND THE HURONIAN SUPERGROUP (ONTARIO): GLACIOGENICS, PALEOSOLS, AND ORTHOQUARTZITES

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In the Early Proterozoic Marquette Range Supergroup of the Upper Peninsula of Michigan, subvertical diamictite and dropstone-bearing units that unconformably overlie Archean basement (the Fem Creek Formation of the Iron Mountain area and the Enchantment Lake Formation of the Marquette Trough) have been considered glaciogenic and correlative (Pettijohn, 1943; Gair, 1981; Ojakangas, 1984). Orthoquartzite units which overlie these two units (the Sturgeon Quartzite and the Mesnard Quartzite, respectively) have long been assumed to also be correlative (e.g., Morey, 1972; Young, 1983).

Another basal conglomeratic unit unconformably overlying Archean basement on the northern edge of the Marquette Trough (the Reany Creek Formation) has been interpreted in different ways. A glacial origin has been claimed by Puffett (1960), Gair (1981) and Ojakangas (1984), but Mattson and Cambray (1983) argued for a mass-flow mechanism of deposition without the involvement of glaciers. A possible Archean age was proposed by Small and Bomhorst (1988). Sims (1991) interpreted the Reany Creek as an Archean strike-slip basin fill along a major fault.

The Reany Creek, which tops south, is shown on geologic maps as being in fault contact with both the overlying Early Proterozoic Michigamme Slate (Formation) and with sheared rhyolite tuff of the Archean Mona Schist. However, recent field work has verified an observation by Puffett (1974, p. 23) that a quartzite mapped as uppermost Reany Creek might someday be proven to belong to a different formation. I contend that this unnamed quartzite is a remnant of a faulted-out overlying quartzite unit that is correlative with the Sturgeon and Mesnard Quartzites.

The Fern Creek Formation is overlain by the Sturgeon Quartzite. A two-meter thickness of sericite schist is exposed locally just beneath the Sturgeon Quartzite and it was suggested by Trow (1948) that it represents a zone of weathered Fem Creek. A similar sericite schist is interbedded with quartzite in the uppermost Enchantment Lake Formation near the contact with the overlying Mesnard Quartzite. Similarly, in the upper Reany Creek, sheared sericite schist is present beneath the unnamed quartzite unit mentioned above. The sericite schists between the three glaciogenic units and the overlying quartzites are herein interpreted to be metaregolith (i. e., paleosol or reworked paleosol) formed upon the glaciogenic units. The overlying quartzites are interpreted to be products of the erosion and reworking of a deeply weathered cover of glaciogenic material (i.e., the paleosol) that was present on the Early Proterozoic land surface. The tripartite sequence of glaciogenic rock, paleosol, and quartzite in three areas of the Upper Peninsula of Michigan is thus interpreted as erosional remnants of what was once a widespread and likely continuous sequence. This similarity in lithology, stratigraphy, and interpreted history is herein cited as strong circumstantial evidence that the three sequences are indeed correlative.

The Huronian Supergroup 200 km to the east in Ontario contains three glaciogenic units—the Ramsay Lake, the Bruce, and the Gowganda Formations (e.g., Young, 1981a, 1981b). The uppermost, the Gowganda, has been correlated with the Michigan units (e.g., Puffett, 1969; Young, 1970, 1983; Ojakangas, 1988). Description of an interpreted paleosol within the Lorrain Formation that overlies the Gowganda is in preparation by K. Card, J. Marmo, and R. Ojakangas; this paleosol is being interpreted as correlative with those in Michigan. Young (1983) emphasized that the Michigan sequences of glaciogenic rock, quartzite, and overlying dolomite (e.g., Kona Dolomite) can be correlated with the Ontario sequence of Gowganda, Lorrain, and Gordon Lake Formations. Recent C isotope studies have also been used as evidence for correlation of carbonate units in the described sequences as well as correlation with Early Proterozoic carbonate units in Wyoming (Bekker et al., 1996). Correlation with similar Early Proterozoic sequences in Finland and Russia was proposed earlier (Marmo and Ojakangas, 1984; Ojakangas, 1985, 1988) and the possible existence of an Early Proterozoic supercontinent has been proposed (Ojakangas et al., 1991).

The correlation of the upper part of the Huronian Supergroup with the lower part of the Marquette Range Supergroup is steadily being strengthened in spite of the lack of radiometric dates in the Marquette Range Supergroup.

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GIS Applications for Archean Gold Exploration: Using Canadian Mining Camp GIS Queries to Target Gold Exploration in Minnesota

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The objective of mineral exploration is to discover ore mineralization before funding is exhausted or management loses confidence in the exploration team. Exploration tends to use the simplest, cheapest, and lowest risk criteria, methods, and ore deposit models available. However, as mining camps mature and deposits become more difficult to discover, exploration risks increase, and the amount of data potentially applicable to mineral exploration increases. In this case, the exploration geologist must use enhanced exploration methods and ore deposit models, that incorporate additional data, to continue to discover new ore deposits.

Today, vast quantities of geological information are available to the exploration geologist. This information includes field notes and measurements, geological maps, drill hole data, geochemical data, geophysical survey data, remote sensing data, and geologic literature. Geologists must integrate vast quantities of data covering large areas in order to determine the best criteria for effective mineral exploration. Currently, the best method to integrate large data sets is to store all geologic information into a Geographic Information System (GIS). For small areas ($\sim <10\text{km}^2$), simple light-table overlays of geological, geochemical, and geophysical data may be appropriate for interpretation. However, small analog data compilations typically do not answer the larger questions dealing with the fundamental controls on the formation and spatial location of specific types of ore deposits. For Archean mesothermal gold deposits, fundamental mineral exploration questions include:

Which greenstone belt should be explored?

Where in the greenstone belt should exploration be concentrated?

What are the best criteria for target selection in the concentrated exploration area?

Geologic compilations have been converted into GIS format for the Hemlo, Timmins, and Kirkland Lake gold camps of Ontario. An additional GIS data set from the Cadillac-Bousquet-Malartic gold camp in Quebec is near completion. The GIS data includes geology, 1st 2nd and 3rd order shear zones (Figure 1), faults, alteration, gold mines, gold occurrences, ore zones, and quartz-gold veins. These GIS data sets are being compared to a similar GIS data set covering 6000 km² of northeastern Minnesota. The goal of the study is to highlight areas of northeastern Minnesota that have geological features similar to those present within the gold camps of Canada.

A series of Archean mesothermal gold deposit *exploration models* have been developed from analyses of the Canadian gold camp GIS data sets. The models are based on unique queries and spatial analyses of structural and lithological attributes that define the location of the major gold deposits in these mining camps. One set of unique queries that defines $< 1\%$ of the total area of the analog mining camps but hosts $> 90\%$ of all gold mined is given below (Figure 2).

- 1) Select compressional jog segments of 1st Order shear zones (Figure 1a)
- 2) Create a 6-kilometer buffer around the selected 1st Order shear
- 3) Intersect all data layers with the 1st Order shear zone buffer
- 4) Within the buffer, select 2nd Order Riedel P shears (Figure 1b,c)
- 5) Create a 200-meter buffer around the selected 2nd Order shears
- 6) Intersect all data layers with the 2nd Order P-shear buffer

Within the GIS environment, the outcome of these queries would be a new subset of geological data that incorporates all aspects of the original data into a much smaller area. The geologist must now use detailed structural, lithological, geochemical, geophysical, and alteration data to target exploration programs in these high potential areas. The Hollinger-McIntyre and Dome mines of the Timmins camp; the Kerr Addison, Upper Canada, and the Kirkland Lake Main Break mines of the Kirkland lake gold camp; and all of the Hemlo gold mines are defined by the simple queries listed above. Similar queries are being applied to the Minnesota GIS to outline areas with high potential for hosting large Archean gold deposits.

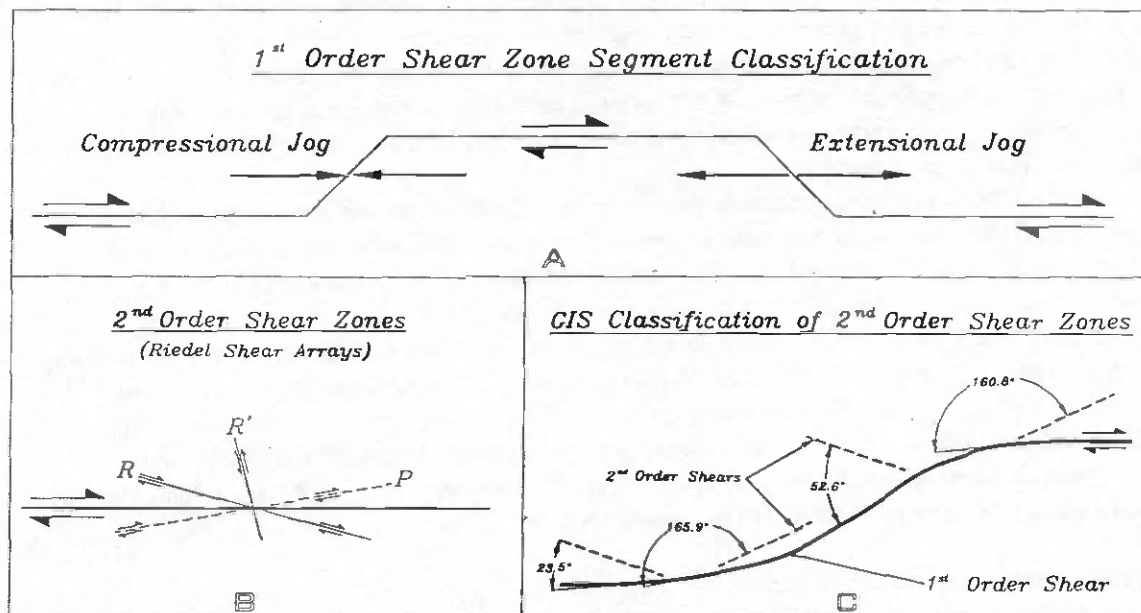


Figure 1. A) Classification of 1st order shear zone segments
B) 2nd order shear zone classification based on Riedel shear arrays
C) GIS methodology for 2nd order shear zone classification

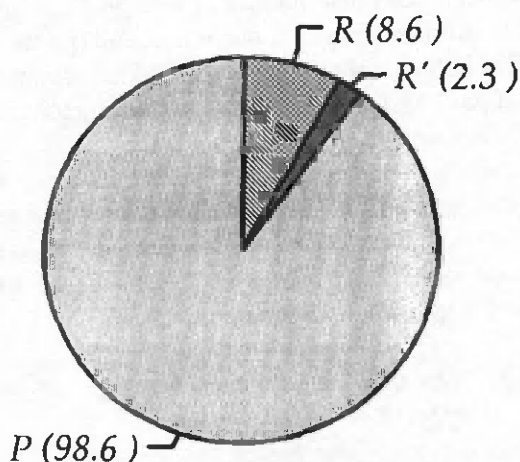


Figure 2. Correlation of mined gold and 2nd order shear zone classification for the Timmins, Kirkland Lake and Hemlo Gold Camps. Values in millions of ounces of gold.

RE-OS, SM-ND, AND Pb ISOTOPIC CONSTRAINTS ON MANTLE AND CRUSTAL CONTRIBUTIONS TO
MAGMATIC SULFIDE MINERALIZATION IN THE DULUTH COMPLEX.

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Previous petrologic and stable isotopic studies of sulfide mineralization in the Duluth Complex have led to the premise that sulfide genesis is strongly linked to the interaction between mantle-derived magmas and sedimentary country rocks in a rift zone environment. In order to more fully evaluate the nature of this interaction, and to gain an insight into the possible importance of externally-derived metals in the ore-forming process, Pb, Sm-Nd, and Re-Os isotopic studies of the Babbitt Cu-Ni deposit were initiated. Rock-types examined include low-sulfide troctolite that show very little petrologic evidence for contamination, disseminated sulfide-bearing troctolitic to gabbroic rocks that occur close to the basal contact with country rocks and contain metasedimentary xenoliths, and massive sulfide. Pb isotopic values of whole rocks, plagioclase mineral separates, and massive sulfides show only subtle differences, and are compatible with 3 to 5% contamination of a mantle-derived melt with a Proterozoic crustal contaminant. ϵ_{Nd} (1.1 Ga) values of the troctolite and gabbro samples are chondritic, and only the massive sulfides show strong evidence for contamination based on Sm-Nd isotopic values. Massive sulfides tend to be more sensitive indicators of contamination in the Sm-Nd system because of late-stage incorporation of a light rare earth element-rich fluid into a Ca-PO_4 (apatite) component of the immiscible sulfide liquid. γ_{Os} (1.1 Ga) values are also strongly anomalous, and range from ~500 to 1300 in disseminated sulfide-bearing troctolites and massive sulfides. These values are also consistent with from 3 to 5% contamination by Proterozoic sedimentary rocks. Elemental and isotopic mass balance calculations suggest that from 30 to 60% of the Pb and Os in the sulfide mineralization have been derived from external sources. A corollary is that other metals may also be in part derived from external sources, which would aid in explaining the compositional diversity of the sulfide mineralization. Selective assimilation of country rocks by mantle-derived magmas may occur in crustal staging chambers, during ascent to shallower levels, or in situ as a result of devolatilization reactions and partial melting.

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The Tectonic, Magmatic and Mineralization History of the Sudbury Structure

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The Sudbury Structure consists of three major components: 1) the Sudbury Basin; 2) the Sudbury Igneous Complex (SIC) which surrounds the basin as an elliptical collar; and, 3) an outer zone of shatter-coned and brecciated footwall rocks. The area has gained fame as a result of the SIC and the Ni-Cu-PGE ores which it hosts, as well as the proposed meteorite impact origin for the structure (Sudbury Event). However, the area has undergone several significant Archean-Proterozoic tectonic, magmatic and mineralization events which have been largely overshadowed by the Sudbury Event.

The Sudbury area was shaped by two Wilson cycles of crustal extension and closure, namely a Paleoproterozoic cycle and a Mesoproterozoic cycle. The Sudbury Structure was apparently the site of a triple junction or hot-spot during these cycles. The first cycle, from 2500 to 1700 Ma, included the following events: doming (uplift of Levack gneiss complex); NW-SE extension (Matachewan dikes); N-S to NW-SE rifting (faults, mafic intrusions, sedimentation, Ni-Cu-PGE, U); NW-SE extension (Nipissing diabase, Ni-Cu-PGE, Ag, Co); and, NW-SE closure (Penokean Orogeny, 1900-1700 Ma) with imposed meteorite impact (1850 Ma; Ni-Cu-PGE, Zn-Cu-Pb). The second cycle, from 1700 to 1000 Ma, included: N-S extension (alkali metasomatism, Au); N-S extension (hornblende diabase dikes along Murray fault set); NNE-SSW extension (olivine diabase dikes); NE-SW extension (Fecunis Lake fault set); and, NW-SE closure (Grenville Orogeny).

The extensive and rich mineralization which is characteristic of the Sudbury Structure, is related to endogenic and impact-triggered extension and magmatism. Although the Ni-Cu-PGE and Zn-Cu-Pb ore are located within an impact structure, their age and tectonic setting is similar to Ni-Cu-PGE and Zn-Cu-Pb deposits elsewhere in the world. Geochemical arguments have been presented which ascribe the origin of the SIC and its ores to a melt sheet or to contaminated mantle-derived magma. The melt sheet origin divorces the SIC and its ores from their geologic setting and pre-impact history, whereas the SIC and its ores are consistent with evolutionary, global metallogenic events. Meteorite impact is interpreted as a triggering event which focussed long-lived ore-forming processes at Sudbury. If viewed in this manner, layered mafic intrusions and their immediate host rocks, both older and younger than the SIC, warrant further examination to assess their potential for hosting Ni-Cu-PGE ores.

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OVERVIEW OF THE GREGOR GOLDFIELDS CORP. MARATHON (WIRE LAKE) GOLD PROPERTY IN THE HEMLO AREA OF CENTRAL ONTARIO, CANADA

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John Wiebe, President, Gregor Goldfields Corp.

Gregor Goldfields Corp. (Gregor) has been carrying out exploration work on portions of its 4,000 ha Marathon-area property since the ground was first staked in 1983, during the "rush" that followed the 1981 discovery of economic gold mineralization at Hemlo. There is no record of exploration work being carried out on the Gregor property prior to that time. Gold mineralization was first located on the property in 1985 and subsequent programs of diamond drilling have encountered at least four zones or areas of mineralization. The property area is underlain predominantly by mafic volcanic rocks; the auriferous mineralization is associated with zones of intense alteration that occur within these volcanic rocks. Much of the detailed exploration work, especially the diamond drilling, has been carried out in the central area of the property in the vicinity of Wire Lake. The best diamond-drill intersection of gold-bearing mineralization to date is 7.39 g Au/t over 3.04 m while grab samples from surface have returned up to 26.743 g Au/t.

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COPPER AND PRECIOUS-METAL MINERALIZATION IN EASTERN SAULT STE. MARIE MINING DIVISION WITH FOCUS ON THE JENTINA PROPERTY, ALBANEL AND NICHOLAS TOWNSHIPS, DISTRICT OF ALGOMA

John M. Siriunas, P.Eng. and Neil O. Willoughby, NR&J Resource Associates Limited

Copper mineralization in the Huronian Supergroup of central Ontario, though first discovered at Bruce Mines in 1846, has historically been overshadowed in importance by the copper-nickel deposits of the Sudbury area, the paleoplacer uranium deposits of Elliot Lake and the silver-arsenide vein deposits of the Cobalt-Gowganda region.

Previous investigations have postulated a variety of origins for the copper mineralization present within the Huronian. The emerging consensus in economic geology in general is that regional-fault patterns and zones of deformation have played a major role in the formation of metallic-mineral deposits, irregardless of geologic era, and that the recognition of geological structure and alteration can lead to the discovery of significant economic deposits. The fact that most researchers consider the Huronian-Archean interaction to be one of continental collision-subduction zone mechanics invokes epithermal (Cordilleran-type) and mesothermal (Archean-style) models as being applicable to the Huronian Basin.

The Flack Lake Fault is a reverse thrust fault of regional extent that is located along the northern boundary of the Huronian volcano-sedimentary basin. This fault was most likely an active normal fault during the Archean and was re-activated during the Penokean Orogeny. Indications are that the curvilinear, locally east-west trending, Flack Lake Fault System has produced considerable ductile shearing and brittle deformation within the nearby host rocks across the northern Huronian Basin.

Major deposits of structurally-controlled copper and precious-metal mineralization within Proterozoic terranes can be found elsewhere in the world in such settings as northern Australia and Fennoscandia. Within the Huronian Basin of central Ontario, the most well-known occurrences are associated with the Murray Fault, which parallels and lies to the south of the Flack Lake Fault. Copper mineralization in this region has been exploited at Bruce Mines (43,000 t Cu) and the Pater Mine (36,000 t Cu, 140 kg Au, 4,300 kg Ag). A number of copper occurrences are known to be present along the northern margin of the Basin in the vicinity of the Flack Lake Fault; the Bi-Ore Mine at Cobre Lake produced 700 t Cu during its brief period of production (1948-49).

The Jentina Property of A.J. Roy of Sudbury, Ontario, is located in Albanel and Nicholas Townships straddling the Flack Lake Fault. Several copper and precious-metal showings on the Jentina Property are indicated to be associated with east-west striking shear and fault zones associated with the main system of faulting. The No. 1 zone on the Jentina Property, as determined from surface mapping, is thought to have a strike length of about 1 km. The zone comprises quartz-carbonate veining with extensive albitization, silicification and chloritization of the host Espanola Formation; massive sulphide (chalcopyrite-bornite) mineralization is locally present. The No. 2 zone is about 1½ km in length. This zone includes quartz veining, breccias and stockworks. Considerable chloritization and silicification occur while albitization is limited. Scattered pods of massive chalcopyrite occur within this zone which transgresses several lithologies. On the Canamiska section of the claim block, a 3 km-long soil geochemical and conductive geophysical anomaly has been drill-tested for only 75 m of its strike length. Intersections of up to 1.44% Cu over 19.5' (5.9 m) were encountered during that drill program in 1965.

Regional studies within NTS Sheet 41J have demonstrated that the available lake sediment geochemistry and airborne geophysics, especially magnetics, can be used as effective tools to map geological structures and be used to locate other areas, similar to the Jentina, that are favourable targets for mineral exploration in the region.

GEOLOGIC MAPPING SYSTEM (GeMS): A DIGITAL APPROACH TO BEDROCK GEOLOGIC MAPPING

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Computers have long been used by geologists to visualize remotely sensed geophysical data and manipulate and image numerical point-source data. Increasingly in recent years, Geographic Information System (GIS) software has been used to produce geologic maps and to archive the raw data on which the maps are based. Little has been done, however, to make use of the exceptional data-management capabilities of GIS for evaluating and sorting geologic, structural, geochemical, and geophysical data, activities that must be done before creating a geologic map. Over the past several years, the Minnesota Geological Survey and other agencies have developed GeMS (Geologic Mapping System), an Arc/Info-based GIS that consists of a graphical user interface, image/grid base layers and data structures for storing and manipulating geologic field and analytical data, and the capability for generating maps. The utility of GeMS as it has been applied to current mapping in the northwestern part of the Duluth Complex will be demonstrated at the poster session.

GeMS has three major goals:

1. To make a system easy to use by both the geologist and the potential user. GeMS has a menu-driven, point-and-click interface for data entry, retrieval, manipulation, and imaging. This reduces the time needed to learn how to use GIS software and allows geologists to focus on using GIS as an aid in making geologic interpretations.
2. To develop a flexible data-base structure that accommodates the subjective nature of most field data, the nonuniformity of nomenclature, and the unique mapping styles of individual geologists, while permitting the straightforward retrieval and sorting of that diverse and descriptive information.
3. To allow for expansion and upgrading of the system without rendering prior data bases obsolete. GeMS may always remain a work-in-progress, as new users identify modifications to better suit their style of mapping or to better describe a particular geologic terrane.

The basic structure of GeMS consists of five general functions (Fig. 1): (1) selection of the mapping area, base maps, and overlays [SETUP]; (2) addition and modification of basic geologic data [OUTCROP, SAMPLES, and STRUCTURE]; (3) manipulation of the data using sorting, statistical, and imaging tools [TOOLS]; (4) geologic interpretation [GEOLOGY], and (5) map plotting [PLOT]. This basic structure is outlined in the startup menu of GeMS.

Choices of the mapping area, base maps, and transparent overlays for all other GeMS operations are made through the SETUP function. The standard base for detailed bedrock geologic mapping in Minnesota is the USGS 1:24,000-scale (7.5') topographic quadrangle map, which is available in digital-raster-graphic and digital-elevation-model formats. Low-altitude orthophotoquads and geophysical anomaly images (aeromagnetic and gravity) are also available. Transparent overlays can include outcrop patterns, sample locations, structure symbols, and other point- and line-source data.

Basic field and analytical data are entered in three geologic data layers—OUTCROP, SAMPLES, and STRUCTURE. Data layers are constructed to be menu-driven, whereby the user selects from a look-up table the most appropriate term for a particular attribute. The outcrop-data layer records the physical characteristics of an outcrop. Attributes of three rock types per outcrop may be entered through one of four menu-driven tables, which have been customized to permit description of intrusive-igneous, volcanic, sedimentary, and metamorphic rocks. The sample

layer records the physical state of the sample and the types of analyses conducted on it (e.g., petrographic, microprobe, geochemical (whole-rock, isotopic, and assay), geophysical properties, geochronologic). These data are stored in associated files and are indexed to a unique sample identifier. The structure layer records the type of linear or planar feature and its orientation; standard symbols are assigned to each type. A fourth data layer containing drill-hole information will be added soon, and field photographs may constitute a fifth layer at a later date.

The TOOLS function provides subroutines for sorting, numerical manipulation, and imaging of data from the three geologic data layers and related data tables. This function is still being developed, but will include options like color coding of outcrops by specified attributes, and the calculation and plotting of the values of geochemical parameters (e.g., Fo in olivine, trace-element ratios, normative abundances).

The GEOLOGY layer provides for the creation and description of map units (polygons), unit contacts (polygon edges), and linear features like faults (lines).

Lastly, the PLOT function permits layout and scaling of printed maps to include any combination of base material, raw or processed data, and geologic interpretations.

The continuing evolution of GeMS offers an increasingly useful tool for the collection and manipulation of geologic information, map production, and, most importantly, interpretation of bedrock geology. GeMS can be used from the beginning of a mapping project to the final map creation and allows for straightforward upgrades with future acquisitions of data. In addition, users have easy access, in a geographic context, to *all* the original information on which a map interpretation is based.

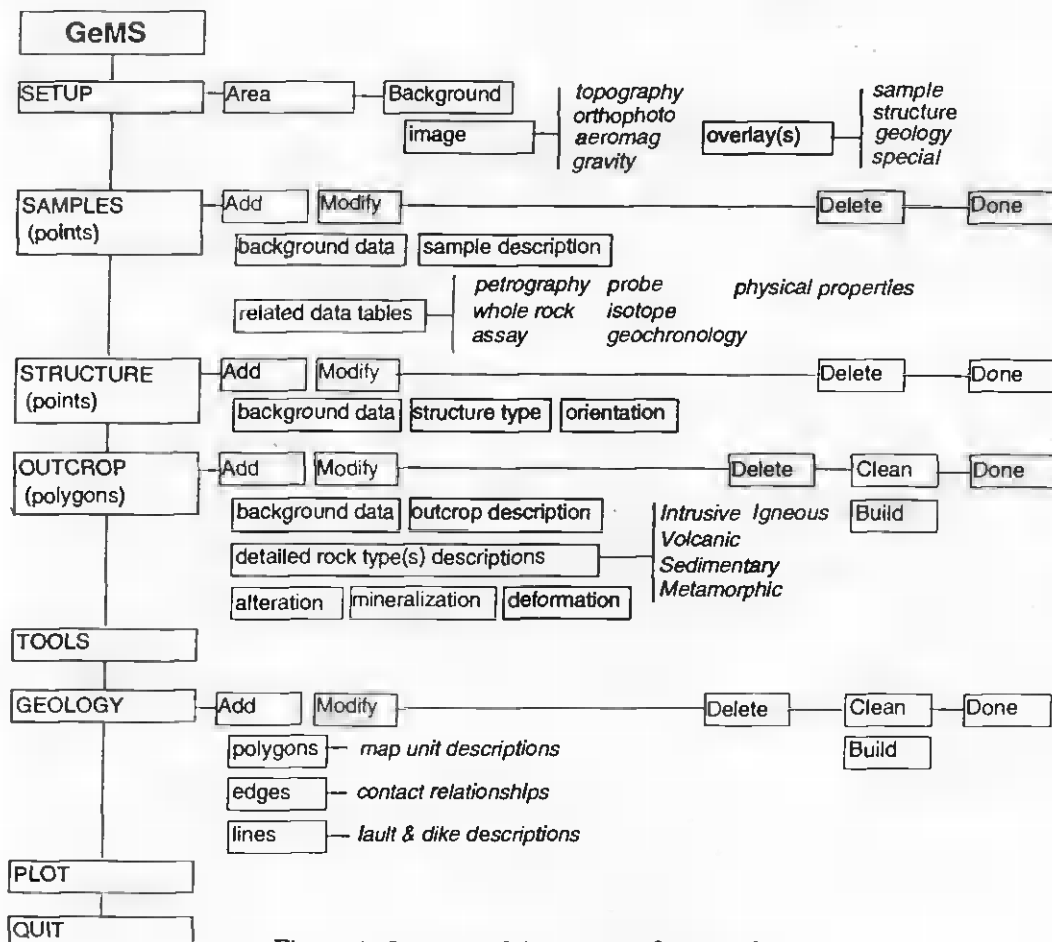


Figure 1. Conceptual framework for GeMS

HYDROGEOLOGY OF SALINE- AND BORON-BEARING GROUND WATERS IN THE NORTH SHORE VOLCANIC GROUP, MINNESOTA

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Public concern grew in late 1994 along the North Shore over high levels of boron in ground water. The LTV Mining Company, which owns a large coal burning operation near the town of Schroeder, initiated a study to determine whether boron in ground water was from the plant's fly ash piles or from natural sources. The resulting report(6) shows that boron is at levels above the recommended allowable limit of 300 ppb in ground water all along the North Shore and concluded that it is coming from natural sources. In addition, the LTV study sampled two wells that were highly saline, with chloride concentrations greater than 40,000 ppm. The LTV report raised two questions about the composition of ground water along the North Shore: 1—What is the geologic source of the boron? and 2—What is the distribution and origin of the saline water? This study uses chemical and isotopic analysis of ground water, combined with new information on the shape and evolution of the Portage Lake volcanic basin(1,5) to propose that the saline water resides under the lake, at least in part within a thick (>40 m) interflow sedimentary unit located stratigraphically at the base of the youngest basalts of the middle Proterozoic North Shore Volcanic Group (NSVG). Allen, D.E., et al. (this vol.) describe a possible model for the dissolution of boron in ground water and offer evidence for the presence of marine waters in the rift basin. The preliminary data suggest that boron and the occurrence of saline waters along the North Shore are genetically related.

The primary source of water for wells are fractures within the basalts of the NSVG. Typical yields for these wells are 2-4 gallons per minute. Wells finished in the interflow sedimentary rocks generally have higher yields due to the greater permeability of these strata. Interflow sedimentary units typically are no more than a few meters thick(3). Notable exceptions are the 70-m-thick unit exposed at Good Harbor Bay and an approximately 40-m-thick polymict conglomerate partially exposed near Little Marais (Fig. 1).

The Good Harbor Bay unit is composed of medium- to coarse-grained sandstone grading into interbedded fine- to medium-grained well-sorted sand and shale beds; the unit becomes increasingly shaly near the top. The beds in the interflow rocks and the overlying basalts dip 10-15 degrees to the south-southeast (Fig. 1). The polymict conglomerate near Little Marais, like the Good Harbor Bay interflow unit, is structurally conformable with the overlying Schroeder-Lutsen basalts. The LTV study demonstrated that the water from wells finished in both sedimentary units contain boron. In addition, two wells sampled near Little Marais as part of the LTV study had chloride levels greater than 40,000 ppm. These sites were chosen for additional water and rock sampling because the units could be sampled from outcrop, and a reasonable conceptual model could be constructed to demonstrate the path of ground-water flow to the wells.

Although the Little Marais and Good Harbor Bay units have not previously been correlated, their similar stratigraphic position and uncommon thickness imply that these units were deposited at the same time. Furthermore, the location of these units relative to the shape of the Portage Lake volcanic basin, as proposed by Allen, D.J., et al.(1), fits a model of high energy deposition along the cusp of the basin (Little Marais) and lower energy deposition farther from the basin's edge (Good Harbor Bay). A broad seismic reflector at the base of the Schroeder-Lutsen basalts supports this depositional model(1). From a hydrostratigraphic perspective, correlation of the two units provides for a laterally extensive, porous aquifer extending along the shore and beneath the lake.

A positive linear correlation exists between dissolved bromide and chloride concentrations in the sampled ground waters from Little Marais and Good Harbor Bay (Allen, D.E., et al.; this vol.). The results fit the conceptual model of fresh, dilute waters moving downslope toward the lake mixing with, in the case of the Little Marais sites, saline ground water at or near lake level. At Good Harbor Bay, where no saline water was sampled, the similar bromide-to-chloride ratio may be the result of meteoric waters moving through sedimentary units, which once were saturated with saline water that was compositionally similar to the water at Little Marais. Boron concentrations above 600 ppb were found in the majority of wells sampled at both sites. Boron was also found in

samples from the Good Harbor Bay interflow unit, with concentrations greater than 30 ppm in shaly members. A pH mechanism for the dissolution of boron in ground water from these shaly members is presented in Allen, D.E., et al. (this vol.). Based on their preliminary boron isotopic results, the boron in the Good Harbor Bay interflow sedimentary rocks is thought to be of marine origin, implying the porous interflow sedimentary units at Little Marais and Good Harbor Bay were inundated with sea water at some time during the development of the rift basin.

The presence of seawater is unnecessary to account for saline waters in the rift. Hardie(2) demonstrates how hydrothermal convection and weathering reactions in a closed basin can produce calcium-chloride brines from a wide range of source waters similar to those sampled in this study. However, the heavy boron isotopic signature of the waters analyzed highlights its utility in settings like the rift, where sedimentary evidence for marine environments is inconclusive.

This study suggests several possibilities for further work. The proposed correlation of the Little Marais polymict conglomerate and the Good Harbor Bay interflow unit needs to be investigated. Detailed mapping of the Cascade River area near Good Harbor Bay(9) has revealed a more complex stratigraphy than described in this study. Although not as concentrated, the saline water is chemically similar to the calcium-chloride brines in Michigan copper mines(4; see also refs. to Lane therein). Fluid movement within the basin is currently being modeled(7, 8); these models could be modified to incorporate new information on the shape of the rift and the possibility for a laterally continuous porous unit at the base of the Schroeder-Lutsen basalts.

References: (1) Allen, D.J., et al., 1997, GSA Spec. Paper 312; (2) Hardie, 1990, *AJS*, v. 290, p. 43-106; (3) Jirsa, 1984, *MGS RI 30*, 20 p.; (4) Kelly et al., 1986, *AJS*, v. 286, p. 281-308; (5) Miller & Chandler, 1997, GSA Spec. Paper 312, p. 73-96; (6) STS Consultants, 1995, Eval. of Boron Impacted Wells; report to LTV Steel Mining Co.; (7) Swenson & Person, 1995, IGCP 336, Duluth, Minn., p. 187-188; (8) Woodruff et al., 1995, IGCP 336, Duluth, Minn., p. 213-214; (9) Green, 1996, *Geology on Display*, Minn. DNR, 69 p.; (10) Green, 1982, Two Harbors Sheet, 1:250,000, MGS.

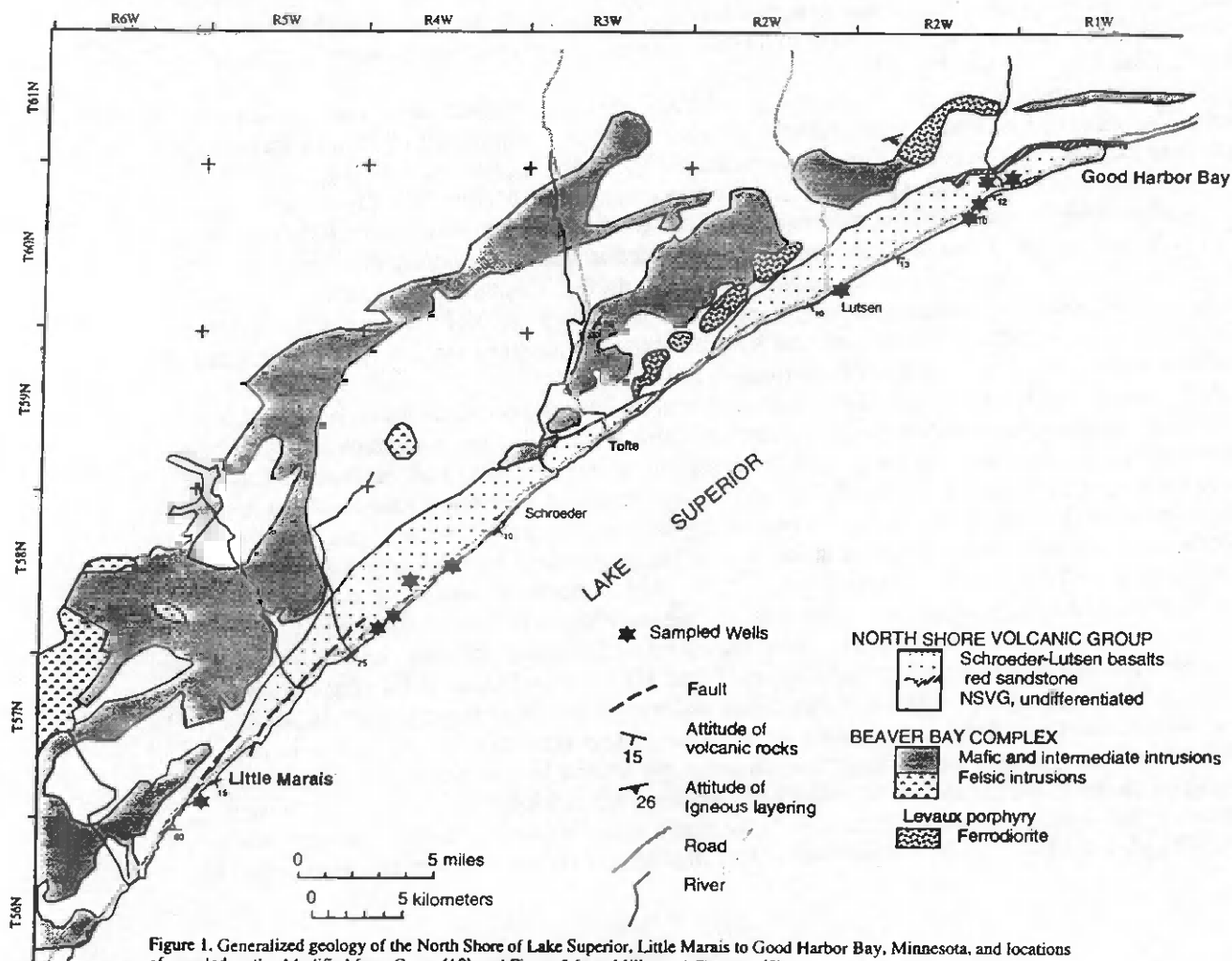


Figure 1. Generalized geology of the North Shore of Lake Superior, Little Marais to Good Harbor Bay, Minnesota, and locations of sampled wells. Modified from Green (10), and Figure 5 from Miller and Chandler (5).

The Greening of Sudbury

Keith Winterhalder

Sudbury lies at the southern edge of the Precambrian Shield, in a vegetation zone transitional between the boreal coniferous forest to the north and the deciduous forest to the south. Prior to the advent of the mining and smelting industry in 1883, the area was characterized by extensive stands of red pine and white pine. One hundred years of logging, fire, soil erosion and enhanced frost action, as well as sulphur dioxide fumigation and copper, nickel and iron particulate fallout from the region's three smelters, severely damaged the Sudbury landscape, giving rise to 10,000 ha of barren land forming concentric zones around the three smelters. The soils of the barren zone are strongly acidified, with pH values ranging from 2.2 to 4.4, and both Cu and Ni levels in the soils of the barren zone are greatly elevated, varying from several hundred to several thousand $\mu\text{g/g}$. As well as solubilizing the Cu and Ni that has accumulated in the soil from atmospheric fallout, the acidity of Sudbury soil releases aluminum ions from aluminosilicate minerals such as clays, contributing to the soil's phytotoxicity. A few stunted, relict individuals of woody plants such as red maple, red oak and aspen can be found on the otherwise barren slopes, which have a stony covering that resulted from the combined action of frost-heaving and erosion on the glacial till-derived soil. Surrounding the barrens is a 36,000 hectare zone of stunted, semi-barren woodland, characterized by patches of bare soil between the relict, coppiced white birch, red maple and red oak.

In the past 25 years, some areas of previously barren soil have been colonized by species such as tufted hair grass, tickle grass and dwarf birch, as a result of the evolution of metal-tolerant ecotypes. Furthermore, since the closure of the Coniston smelter in 1972, there appears to have been some natural amelioration of pH and metal levels in that vicinity, and less metal-tolerant plant such as white birch and wavy hairgrass have begun to colonize the area.

The announcement by Inco Ltd. in 1969 of its intention to construct a 381 m smokestack stimulated the Ontario Department of Lands and Forests and Laurentian University to initiate a joint experimental tree-planting program. The trees planted on the barrens showed almost total mortality, but it was found that the soil could be detoxified sufficiently to initiate colonization by the surface-application of ground limestone. Small-scale experiments initiated in 1974 showed that the surface of the

stone-covered soil could be detoxified by the manual application of ground limestone, and that seeds were trapped by the stony mulch, and germinated successfully. The open structure of the resulting grassy sward was beneficial for colonization by native plants with wind-blown seeds, since it offered numerous openings and microhabitats for volunteer seedlings. In 1975 and 1977, small groups of elementary school pupils successfully established grass on small patches of barren land near their schools, using this approach.

In 1978, the Regional Municipality of Sudbury applied for job-creation funds to employ one hundred and seventy-four post-secondary students to carry out large-scale revegetation employing the same technique. The program reached its peak in 1983, when 1,277 unemployed persons were employed on combined federal, provincial, municipal and industry funding. So far, approximately 3,500 ha of land have been greened in this way. More recently, Inco has employed a commercial crop-dusting company to apply limestone, fertilizer and seeds from the air..

Spontaneous colonization of the grassed land by larger woody plants is so far confined to birch, poplar and willows, because conifer seed source is scarce and the seed bed conditions are poor. More than 2.5 million native trees, mostly Jack pine, red pine and white pine which were the dominant species of the pre-disturbance landscape, have been planted since 1978 in small informal groups, which break up the monotony of the winter landscape, and form a seed source for future spread.

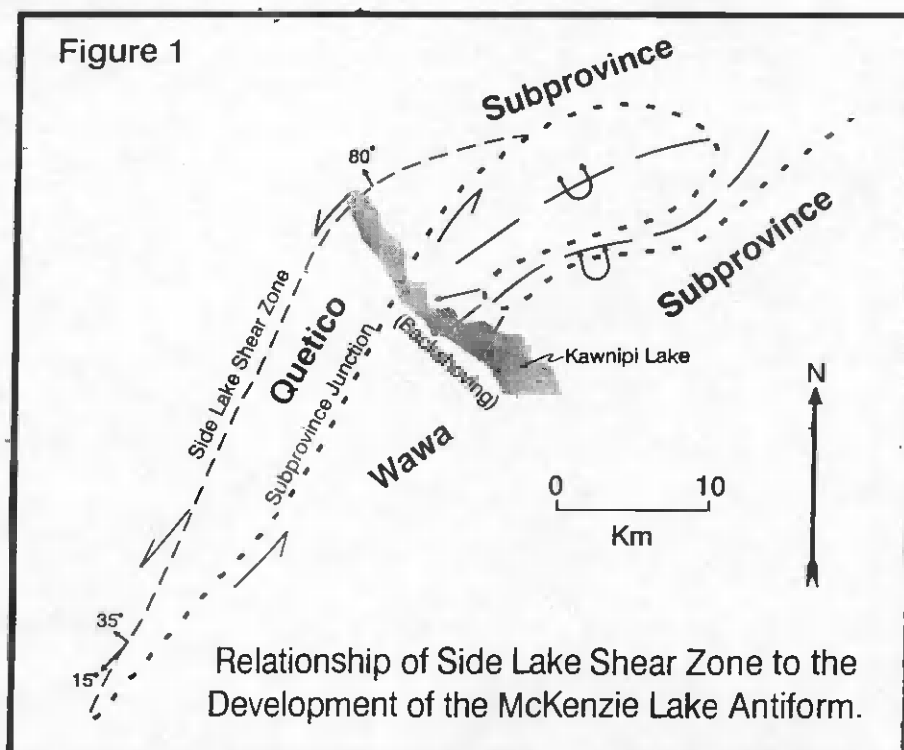
Plant communities that results from the revegetation procedure contains components derived from the seed mixture, planted trees, the seed rain, and any metal-tolerant plants already on site. It is assumed that the landscape will ultimately resemble the original pine forest, but concern exists as to how quickly the typical understory species will move in. The usefulness of introducing plugs of soil that contain desirable understory species, a seed bank, and soil microorganisms is currently under investigation, and is meeting with some success. Another current area of interest is the use of liming and revegetation on a watershed basis, thus solving the dual problems of barren land and acidified lakes.

Unique features of the Sudbury program include the minimal amelioration approach, in which natural recolonization plays a critical role, and the strong manual component and resulting job-creation benefits.

THE MCKENZIE LAKE ANTIFORM AND THE KAWA BAY SYNFORM, QUETICO PROVINCIAL PARK, ONTARIO

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The McKenzie Lake antiform occurs in the northeastern part of Quetico Provincial Park. It was formed by late-stage transpression, which produced ductile deformation of the Quetico-Wawa subprovince boundary. The fold measures at least 18 km along its axial strike and is about 5 km in maximum outcrop width. The crest of the fold defines the subprovince junction and arches through a distance of about 16 km; its hinge, which does not correspond to the crest, is very sharp. Both limbs dip steeply northwest, and the underlying Kawa Bay synform is very tight, severely stretched and dismembered, but still traceable in outcrop and on aerial photographs (see Fig.1). Although the plunge of the McKenzie Lake structure is to the northeast, the degree of plunge is not easily measured. Lineation on slickensided surfaces plunges gently southwest on the related Side Lake zone of backthrusting, and this suggests that the folds plunge steeply northeast. The Side Lake shear zone emanates from the crest of the antiform as a southwest-trending backthrust which exhibits left-lateral sense of shear. About 28 km to the southwest, the Side Lake shear zone cuts a portion of the undeformed Lac La Croix leucogranite which is dated at $2,662 \pm 5$ Ma (Woodard and others, 1995). This age is approximately 30 my younger than the folded tonalite sills (2694 ± 1 Ma) of the Wawa subprovince, and 15 my younger than the folded quartz monzonite sills (2678 ± 6 Ma) in adjacent portions of the Quetico subprovince. The southwest hinge area of the underlying Kawa Bay synform is cut by a stock-like body of undeformed granite, and an age for this granite should allow determination of the time the junction was folded. The southwest hinge and trough area of the Kawa Bay synform is broken into a mega-breccia, and major fold axes, which were developed in Wawa subprovince rocks during an earlier phase of the juxtaposition, are secondarily folded into many open folds whose axes are randomly oriented. This secondary deformation appears to have been accomplished by a process we call "backshoving" where the trough area of the Kawa Bay synform is squeezed backward (toward the southwest) under the northeastward overriding-mass of the McKenzie Lake antiform (see Fig. 1).



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AGE CONSTRAINTS ON PLUTONISM, METAMORPHISM AND DEFORMATION ACROSS THE WAWA-QUETICO SUBPROVINCE BOUNDARY NEAR THE MANITOUWADGE GREENSTONE BELT, NORTHWESTERN ONTARIO

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The volcano-plutonic Wawa subprovince and the metasedimentary-migmatitic Quetico subprovince represent first order subdivisions of the Superior Province; yet our work along the Wawa-Quetico boundary and in the Manitouwadge greenstone belt (MGB) shows that most of the structural and metamorphic history is common to both terranes, and that Quetico greywackes are correlative with greywackes in the MGB. The Manitouwadge greenstone belt (MGB) is a highly deformed remnant of supracrustal rocks comprising a mafic-to-felsic volcanic succession of ca. 2720 Ma, the felsic component of which is intercalated with iron formation and associated massive sulphide deposits. A synvolcanic trondhjemite was both a magma reservoir for felsic volcanism and a heat source for mineralizing hydrothermal activity. U-Pb ages of detrital zircons from greywackes in the MGB, and in the southern Quetico subprovince immediately to the north, constrain the depositional ages of both sedimentary packages to younger than ca. 2690 Ma and support their correlation. The Everest Lake pluton intrudes the Quetico greywackes along the subprovince boundary. The age of the Everest Lake pluton constrains the minimum depositional age of the Quetico greywackes to older than ca. 2680 Ma. The new ages from the southern Quetico, in combination with previous work in the northern Quetico (Davis et al., 1990), show that Quetico sediments were deposited over at least ca. 10 m.y. and are consistent with southward younging, a test proposed by Percival and Williams (1989) for their accretionary prism model of the Quetico subprovince.

Regional metamorphic grade increases northward, from upper amphibolite facies without migmatization in the southern MGB, to granulite facies north of the Wawa-Quetico boundary, with extensive migmatization in the southern Quetico and northern Wawa subprovinces. Regional structural evolution can be modelled by a four-phase sequence of ductile deformation. In the MGB, D2 tectonic fabrics are defined by high grade metamorphic minerals and folded by the D3 Manitouwadge synform, with relatively minor development of D3 fabrics, suggesting that peak metamorphic conditions were attained during D2 deformation. In the Quetico subprovince, migmatitic segregations vary from in situ melts developed in pelitic beds, to discordant foliated and folded pegmatitic and tonalitic dikes, variations that are consistent with protracted migmatization contemporaneous with progressive D2-D3 (and possibly D4) deformation.

Two major syntectonic plutonic events have been documented in the region by U-Pb dating of igneous zircon. Firstly, hornblende-biotite diorite comprising the oldest phase of the Black Pic batholith, and the Loken Lake K-feldspar megacrystic granodiorite, are both ca. 2687 Ma. These plutons were emplaced before or during D2 deformation, based on their strong D2 fabrics which are folded by the D3 Manitouwadge synform. Secondly,

ca. 2677–2680 Ma plutonic rocks, including the Nama Creek K-feldspar megacrystic granodiorite, Banana monzodiorite, and Everest Lake monzodiorite, were emplaced late during D2 or prior to D3 deformation. The Everest Lake monzodiorite intrudes Quetico greywackes and is veined by anatectic segregations, hence constraining migmatization to after ca. 2680 Ma. In the MGB, a tonalite dike which cuts the strong D2 fabric in the Loken Lake pluton, but also has a late-D2 foliation, constrains late D2 to ca. 2675–2680 Ma. Additional younger intrusive rocks, including foliated to nearly massive aplites, granites, pegmatites and lamprophyres, have not been dated.

The distribution of U-Pb titanite ages defines a crude gradient ranging from ca. 2686–2688 Ma south of the MGB, where titanite ages overlap with the ages of igneous zircons, to ca. 2650–2655 Ma in the northern MGB, to ca. 2640 Ma in the Everest Lake pluton in the Quetico subprovince. While our titanite geochronology is still in progress, preliminary indications are that the ages date regional cooling through ca. 600°C, the closure temperature of the U-Pb system in titanite (Heaman and Parrish, 1991). In our work thus far, deviations from the northerly younging pattern are permissive of an interpretation in terms of D3 or D4 deformation of the 600°C cooling surface in the southern MGB after ca. 2655 Ma. Structural relationships and isotopic dating suggest a prolonged migmatization event in the Quetico subprovince, possibly commencing during or soon after the emplacement of the Everest Lake pluton (ca. 2680 Ma), and continuing until ca. 2642 Ma, the age of monazite from a foliated granitic dike interpreted as injected leucosome of local derivation.

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