

42nd Annual



INSTITUTE ON LAKE SUPERIOR GEOLOGY

CABLE, WISCONSIN
MAY 15 - 19, 1996



PROCEEDINGS VOLUME 42
PART 1 - PROGRAM AND ABSTRACTS

42ND ANNUAL MEETING INSTITUTE ON LAKE SUPERIOR GEOLOGY

Volume 42 consists of:

Part 1: Program and Abstracts

Part 2: Volcanogenic Massive Sulfide Deposits of Northern
Wisconsin: A Commemorative Volume

Part 3: Field Trip Guidebook

1. Glacial geology of western Wisconsin
2. Geology of the Montreal River Monocline:
A traverse through 25 km of the crust
4. Early to Middle Proterozoic geology of the Lake
Namekagon region
5. Lake Namekagon and Penoque Gap areas, west
Gogebic Range, Wisconsin

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

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INSTITUTE ON LAKE SUPERIOR GEOLOGY

42ND ANNUAL MEETING

MAY 15 - 19, 1996

CABLE, WISCONSIN

SPONSORED BY:

U. S. GEOLOGICAL SURVEY

AND

UNIVERSITY OF WISCONSIN - OSHKOSH

PROCEEDINGS

VOLUME 42

PART 1 -- PROGRAM AND ABSTRACTS

EDITORS:

LAUREL G. WOODRUFF, U. S. GEOLOGICAL SURVEY, ST. PAUL, MN

SUZANNE W. NICHOLSON, U. S. GEOLOGICAL SURVEY, RESTON, VA

CONTENTS

Part 1 Program and Abstracts

Institutes on Lake Superior Geology to 1996	i
Constitution of the Institute on Lake Superior Geology	ii
By-Laws of the Institute on Lake Superior Geology	iii
Index of Proceedings Volumes and Field Trip Guidebooks	iv
Award Guidelines for Sam Goldich Medal	ix
Board of Directors	x
Local Committees	x
Student Paper Committee	xi
Session Chairs	xi
Goldich Medal Committee	xi
1996 Goldich Medal Recipient	xii
Past Goldich Medalists	xii
Banquet Speaker	xii
1996 Goldich Medal Recipient Citation	xiii
Student Travel Award	xv
Report of the Chair of the 41st Annual Institute	xvi
Calendar of Events and Program	xxi
Abstracts	1

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, Minnesota	D.L. Southwick
29	✓ 1983	Houghton, Michigan	T.J. Bornhorst
30	✓ 1984	Wausau, Wisconsin	G.L. LaBerge
31	1985	Kenora, Ontario	C.E. Blackburn
32	✓ 1986	Wisconsin Rapids, Wisconsin	J.K. Greenberg
33	1987	Wawa, Ontario	E.D. Frey & R.P. Sage
34	✓ 1988	Marquette, Michigan	J. S. Klasner
35	1989	Duluth, Minnesota	J.C. Green
36	1990	Thunder Bay, Ontario	M.M. Kehlenbeck
37	1991	Eau Claire, Wisconsin	P.E. Meyers
38	1992	Hurley, Wisconsin	A.B. Dickas
39	1993	Eveleth, Minnesota	D.L. Southwick
40	1994	Houghton, Michigan	T.J. Bornhorst
41	1995	Marathon, Ontario	M.C. Smyk
42	1996	Cable, Wisconsin	L.G. Woodruff

CONSTITUTION OF THE INSTITUTE ON LAKE SUPERIOR GEOLOGY

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

Article VIII Amendments

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

BY-LAWS

I. Duties of the Officers and Directors

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

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

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

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

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

II. Duties and Expenses

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

III. Rules of Order

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

IV. Amendments

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

INDEX OF PROCEEDINGS VOLUMES AND FIELD TRIP GUIDEBOOKS OF THE INSTITUTE ON LAKE SUPERIOR GEOLOGY 1955-1996

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)

VOL. YEAR LOCATION

- 1 1955 MINNEAPOLIS, MINNESOTA
Program and Abstracts (contains no record of field trips)
- 2 1956 HOUGHTON, MICHIGAN
Program and Abstracts
Geological Exploration (inferred to be a field guide)
- 3 1957 EAST LANSING, MICHIGAN
Program and Abstracts
- 4 1958 DULUTH, MINNESOTA
Program and Abstracts
- 5 1959 MINNEAPOLIS, MINNESOTA
Program and Abstracts
- 6 1960 MADISON, WISCONSIN
Program and Abstracts
- 7 1961 PORT ARTHUR, ONTARIO
Program and Abstracts (misprinted label reads 6th annual meeting)
- 8 1962 HOUGHTON, MICHIGAN
Program and Abstracts
- 9 1963 DULUTH, MINNESOTA
Program and Abstracts
Field Itinerary: Stratigraphy of the Biwabik Iron Formation.
- 10 1964 ISHPEMING, MICHIGAN
Program and Abstracts
Field Trip: Marquette iron-mining district and Republic trough
- 11 1965 ST. PAUL, MINNESOTA
Program and Abstracts
Field Trip Guide to the St. Cloud granite district, central Minnesota
- 12 1966 SAULT STE. MARIE, ONTARIO
Program and Abstracts includes field guides to:
 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
- 14 **1968 SUPERIOR, WISCONSIN**
Technical Sessions and Abstracts
Guide for Field Trip in the Duluth Complex near Ely, Minnesota
- 15 **1969 OSHKOSH, WISCONSIN**
Technical Sessions and Abstracts
Guidebook: Central Wisconsin volcanic belt
- 16 **1970 THUNDER BAY, ONTARIO**
Technical Sessions, Abstracts and Field Guides 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**
Technical Sessions, Abstracts and Field Guides 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**
Part I. Technical Sessions-Agenda and Abstracts (describes trips A-D)
Field Trips:
 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**
*Technical Program and Abstracts**
Field Trip: Guidebook to the geology and mineral deposits of the central part of Jackson County and part of Clark County, Wisconsin (WGNHS)
Field Trip: Guidebook to the Precambrian geology of northeastern and north-central Wisconsin
Field Trip: Guidebook to the upper Mississippi Valley base-metal district (WGNHS Information circular No. 16)
Bibliography of Current Research in the Lake Superior Region
- 20 **1974 SAULT STE. MARIE, ONTARIO**
Field Trip 1: Middle Keweenawan rocks of the Batchawana-Mamainse Point area
Field Trip 2: unknown
Field Trip 3: Precambrian igneous rocks of the north shore of Lake Huron region
Field Trip 4: Stratigraphy and sedimentation of the Huronian Supergroup
Field Trip 5: The Michipicoten greenstone belt
Bibliography of Current Research in the Lake Superior Region (First Supplement)
- 21 **1975 MARQUETTE, MICHIGAN**
Proceedings
 Includes the following field trip guides and a supplement by Burton Boyum containing a color map of the Marquette Mineral District:
 1. Glacial geology (trip canceled, 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**
Proceedings
 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**
Proceedings
 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**
Abstracts and Proceedings
 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 (WGNHS Field Trip Guide Book Number 2)
- 25 1979 **DULUTH, MINNESOTA**
Technical Sessions and Abstracts 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**
Proceedings and Abstracts
 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**
Abstracts and Proceedings
 Field Excursion Guide The Huronian rocks between Sault Ste. Marie and Thessalon, District of Algoma, Ontario
- 28 1982 **INTERNATIONAL FALLS, MINNESOTA**
Proceedings: Abstracts and Field Trips (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**
Abstracts
Field Trip 1 Guide to the geology of the Early Proterozoic rocks in northeastern Wisconsin
Field Trip 2 Early Proterozoic tectonostratigraphic terranes of the southern Lake Superior region
Field Trip 3 The Wausau Syenite Complex
- 31 1985 **KENORA, ONTARIO**
Abstracts
Field Trip Guidebook
 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**
*Abstracts**
Field Trip I The Wolf River Batholith and Baraboo interval (published as Field Trip Guide Book Number 12, Wisconsin Geological and Natural History Survey)
Field Trip II Penokean deformation and metamorphism in central Wisconsin: volcanic rocks and gneisses (published as un-numbered Field Trip Guide Book of the Wisconsin Geological and Natural History Survey)
- ☞ (compiler note: new reference designations were adopted to conform to ISSN standards in 1987)
- 33 1987 **WAWA, ONTARIO**
*Part 1: * Abstracts*
*Part 2: * Geology of the Wawa area and gold mineralization*
*Part 3: * Geology and stratigraphy of the Michipicoten Iron-Formation*
*Part 4: * Geology of the Hemlo Deposit*
*Part 5: * The Kapuskasing Uplift: Archean greenstones and granulites*
- 34 1988 **MARQUETTE, MICHIGAN**
*Part 1: * Abstracts*
Part 2: Field Trip Guidebook
 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**
Part 1: Abstracts
Part 2: Field Trip Guidebook
 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**
Part 1: Abstracts
Part 2: Field Trip Guidebook
 1. Mafic intrusions, PGE mineralization, and granitoid rocks of Lac des Illes 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**
 *Part 1: * Abstracts*
 *Part 2: * Field Trip Guidebook*
 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
- 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, Field Services Section, Suite B 002, 435 South James Street, Thunder Bay, Ontario Canada, P7E 6E3, Phone: 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
- Future Meeting Locations:**
- 43 **1997 SUDBURY, ONTARIO**
- 44 **1998 KENORA, ONTARIO**

AWARD GUIDELINES SAM GOLDICH MEDAL

Preamble

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

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

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

Award Guidelines

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

April 4, 1981

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

BOARD OF DIRECTORS

- 1996 Laurel G. Woodruff, Chair**
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
- 1993 David L. Southwick**
Minnesota Geological Survey, St. Paul, Minnesota
- Permanent Secretary-Treasurer**
Mark Jirsa
Minnesota Geological Survey
2642 University Ave.
St. Paul, MN 55114-1057
-

LOCAL COMMITTEES

GENERAL CHAIR

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U. S. Geological Survey, St. Paul, Minnesota

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U. S. Geological Survey, St. Paul, Minnesota
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Minnesota Geological Survey, St. Paul, Minnesota

Suzanne Nicholson

U. S. Geological Survey, Reston, Virginia

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Consulting Geologist, Rhinelander, Wisconsin

Terry Boerboom

Minnesota Geological Survey, St. Paul, Minnesota

Sidney Hemming

Lamont-Doherty Earth Observatory, Palisades, New York

Mark Jirsa

Minnesota Geological Survey, St. Paul, Minnesota

Suzanne Nicholson

U. S. Geological Survey, Reston, Virginia

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Ontario Geological Survey, Sudbury, Ontario

Klaus Schulz

U. S. Geological Survey, Reston, Virginia

Mark Smyk

Ontario Geological Survey, Field Services Section, Thunder Bay, Ontario

1995-96 GOLDICH MEDAL COMMITTEE

Penelope Morton (1996)

University of Minnesota-Duluth, Duluth, Minnesota

Ken Card (1997)

Ontario Geological Survey (retired), Kanata, Ontario

Dan England (1998)

Eveleth Fee Office, Incorporated, Eveleth, Minnesota

1996 GOLDICH MEDAL RECIPIENT

David L. Southwick
Minnesota Geological Survey
University of Minnesota
St. Paul, Minnesota

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 BANQUET SPEAKER

Steven Kesler
Department of Geological Sciences
University of Michigan
Ann Arbor, Michigan
Sustainable Mineral Development -- Fact or Fiction?

CITATION

David L. Southwick, 1996 S.S. Goldich Medal Recipient

It is my pleasure to introduce to you this evening, David L. Southwick, 17th recipient for 1996 of the Institute's S.S. Goldich medal.

When Laurel Woodruff asked me to make these remarks she prefaced her request by noting that I had worked with Dave on several projects and that I had been around the Institute for many years. Dave and I have worked together for many years and I have been fortunate to have him as a professional colleague and friend. However, having been around the Institute for a long time is nothing more than a matter of luck, and I now find myself writing memorials for friends who were not so lucky. Believe me, this occasion is much more enjoyable.

So who is Dave Southwick? He was born in Rochester, Minnesota in 1936 and graduated from Rochester Senior High School in 1954. He wanted to be a draftsman, but his parents prevailed and he graduated from Carleton College in Northfield, Minnesota with a degree in geology in 1958. From there he went on to graduate school at the Johns Hopkins University where he studied under Aaron Waters. His Ph.D. dissertation had to do with ultramafic rocks in the Cascades of Washington. He wondered about ophiolites long before it was fashionable to do so. After graduate school, Dave started his professional career with the U.S. Geological Survey, Eastern States Branch, in 1962. He returned to Minnesota in January, 1968 having a joint appointment in the Department of Geology and Geophysics at the University of Minnesota and the Department of Geology at Macalester College in St. Paul, Minnesota. He moved to Macalester full-time in 1971 as a Professor of Geology. During that time, Dave worked summers for the Minnesota Geological Survey. He began full-time work with the Survey as a Senior Scientist in 1977, and has been Director of the Survey since 1993 and Professor of Geology in the Department of Geology and Geophysics since 1994. So much for vital statistics.

It goes without saying that receiving the S.S. Goldich medal is a considerable honor. Unfortunately, I do not know what criteria were used by the Selection Committee when they chose to honor Dave. In fact I do not even know who sits on the Selection Committee. Therefore, I will look to the medal itself for guidance. On the reverse side it reads "presented for outstanding contributions to the geology of the Lake Superior region." What does that tell us?

The word "geology" refers to a science and profession dedicated to the study of the history of the Earth. Obviously the science and profession is practiced by geologists. These days some people who study the history of the earth like to call themselves earth scientists rather than geologists. I distinguish the two groups by the fact that geologists make geologic maps. Looking over the list of previous medal recipients, many were first and foremost geologic mappers. Dave has produced a variety of very good

geologic maps while with both the U.S. and Minnesota Geological Surveys. By that criterion Dave is a worthy recipient of the medal.

The word "contributions" on the medal refers—again in my view—to any "body of work" which has advanced geologic knowledge in the region. Again it seems to me that any number of the previous recipients were honored for their "bodies of work" that have included research, teaching, and above all professionalism. Dave has made professional contributions in the areas of both research and teaching. His extensive bibliography covers a wide variety of topics and is frequently cited. More importantly, however, there are any number of younger geologists in the profession who have received basic training under Dave's tutelage. Many of you are in this room! The fact that you are here makes him a worthy recipient of the medal.

The significance of the word "outstanding" is somewhat subjective and a little more difficult to get a handle on. A little history is warranted. The medal is named in honor of S.S. Goldich. Many of you are probably too young to remember Sam. I have the pleasure of knowing him for nearly 40 years. Most of you have heard war stories about him and many probably are true. After my first year in graduate school I decided that my family had forgotten to tell me that my real name was "Morey you stupid ____." In truth Sam was a wonderful man, but he could be tough at times. He was very much like the Drill Instructor we see on TV ads for the U.S. Marine Corps. Sam was tough because he wanted you "to be the best that you can be." He wanted his people to excel—to push the envelope—at whatever they did. He wanted his people to make a difference—he wanted them to be outstanding—to make a difference. Dave has excelled and has pushed the envelope. His structural studies on the Penokean orogen represented a scientific revolution of sorts. His ideas have changed the way many of us think about the rocks—and especially for me about iron-formation. Thus by Sam's creed, Dave is one of those geologists whose body of work has made a difference. All of us are better geologists because of him. I know Sam is pleased and that makes Dave a worthy recipient of the medal. Therefore, I am pleased to present to you the 17th recipient of the S.S. Goldich medal, David L. Southwick.

G.B. Morey
Minnesota Geological Survey
University of Minnesota
St. Paul, Minnesota 55114

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 favored consideration.
- 3) It is desirable for two or more students to jointly request travel assistance.
- 4) In general, priority will be given to those in the Institute region who are farthest away.
- 5) Each travel award request shall be made in writing, to the annual Chairman, with an explanation of need, possible author status or other significant details.

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

41ST ANNUAL INSTITUTE ON LAKE SUPERIOR GEOLOGY MARATHON, ONTARIO

The 41st Annual Institute on Lake Superior Geology was held May 13-18, 1995, in Marathon, Ontario. The meeting was organized by staff of the Ontario Geological Survey, Field Services Section, based in Thunder Bay. Chairman, Mark Smyk, was assisted in the organization of the Technical Sessions by former chairman, Manfred Kehlenbeck of Lakehead University.

The Proceedings of the 41st ILSG was published in six parts:

Part 1: Program and Abstracts (edited by Mark Smyk and Manfred Kehlenbeck)

Part 2: Field Trip Guidebooks

Part 2a: Alkalic rocks of the Midcontinent rift (Ron Sage and David Watkinson)

Part 2b: Geology, structure and age relationships of the Manitouwadge greenstone belt and the Wawa-Quetico subprovince boundary (Eva Zaleski, Virginia Peterson, Hugh Lockwood and Otto van Breeman)

Part 2c: Geology of the Schreiber greenstone assemblage and its gold and base metal mineralization (Mark Smyk and Bernie Schnieders)

Part 2d: Geology and gold deposits of the Hemlo area (Tom Muir, Bernie Schnieders and Mark Smyk)

Part 2e: Kimberlite, base metal and gold exploration using overburden, Wawa area (Tom Morris)

All trips, with the exception of Wawa, were run both as pre- and post-meeting events in order to accommodate large subscription levels and travel schedules. The Hemlo trips spurred the revision and re-publication of a guidebook first published jointly by the Geological Association of Canada, the Mineralogical Association of Canada and the Society of Economic Geologists in 1991. The successful running of the meeting and the associated field trips gave some valuable insight in the planning of a field trip associated with the International Geological Correlation Program in August. Logistical lessons learned in May were put to use when Ron Sage and I led the IGCP delegates through the alkalic rocks of the Marathon area as part of a larger trip looking at intrusive rocks associated with the Midcontinent rift.

There were 145 paid registrants at the 41st ILSG. The nine field trips attracted 163 participants, some of whom were not able to attend the technical sessions.

The annual banquet was attended by approximately 135 delegates. The Goldich Medal, exemplifying outstanding contributions to the understanding of Lake Superior geology, was awarded to Gene LaBerge of the University of Wisconsin, Oshkosh. The award was presented by Tim Flood of St. Norbert College. The banquet speaker was Peter Lightfoot (Ontario Geological Survey, Sudbury) who addressed the relationship between mantle plumes, flood basalts and mineralization.

The Student Paper Award recipients were Geoff Shore (University of Western Ontario) who spoke about alkaline gabbroic rocks of the Coldwell alkalic complex, and Kim Darrah (Kent State University) who presented information on the application of the aluminum-in-hornblende barometer. Five students were given travel awards totaling \$500.

The Board of Directors of the Institute on Lake Superior Geology met in Marathon on May 15, 1995. In attendance were Mark Smyk (1995 meeting chair), Ted Bornhorst (1994 chair and associate secretary-treasurer), Jim Miller (proxy for David Southwick, 1993 chair) and Mark Jirsa (secretary-treasurer). Guests included Laurel Woodruff (chair for 1996 meeting in Cable, Wisconsin), Gene LaBerge (alternate chair for 1996 meeting), Sally LaBerge, Wilf Meyer and Ron Sage (co-chairs for 1997 meeting in Sudbury, Ontario).

The Board of Directors:

1. Accepted Report of Chairman, 40th ILSG meeting
2. Approved Cable, Wisconsin, as host for 42nd ILSG (1996) with Laurel Woodruff as Chair; Gene LaBerge agreed to assist Laurel and take over Chair duties, if need be.
3. Approved Sudbury, Ontario, as host for 43rd ILSG (1997). Wilf Meyer suggested topical sessions and field trips that highlight correlations and contrasts between the Huronian and the equivalent strata in Wisconsin, Michigan, and Minnesota. He further suggested that a session devoted to environmental remediation would be appropriate, and the Board agreed.
4. Accepted ILSG Financial Report (Mark Jirsa and Ted Bornhorst)
5. Approved Gene LaBerge as recipient of 1995 Goldich Medal
6. Approved Dan England as new Goldich Medal Committee member (replacing Glen Adams)
7. Approved motion to allow secretary-treasurers to set reduced prices on back ILSG volumes to reduce inventory and make volumes affordable before their shelf life is exceeded. The motion also allows the secretary-treasurers some lee-way to set those prices to accommodate regional considerations and costs.
8. Approved a motion to donate \$1.00 from each meeting registrant to the Michigan Technological Institute Library to assist in their research and archiving efforts. They maintain the only known full set of ILSG volumes dating back to the Institute's inception in 1955. Donations (\$100-\$150) will be made following the 1996 meeting and every year thereafter.
9. Approved a motion to allow donation of selected back volumes of ILSG Proceedings to the Minnesota Geological Survey (MGS) Library to rebuild their collection after theft.

10. Approved loan of Van Hise and Leith monograph (1911) to a secure section of MGS Library for safe-keeping. The monograph was donated to the ILSG.
11. Discussed "Requirements and Suggestions to Chairpersons." Ted Bornhorst is constructing a manuscript that can be modified with time and passed from chairperson to chairperson. It would detail what must be done by the chair and suggest tips for how to operate a smooth meeting that runs in the black. The board agreed that would be very helpful. It will eventually reside with the secretary-treasurer who will have responsibility to see that it is passed onto the incoming Chair.

12. OTHER BUSINESS

- a. Motion approved to prohibit the use of cameras in both oral and poster sessions, unless the photographer has the permission of individual authors.
- b. Motion approved to require peer review of abstracts. The local chairpersons must establish a review committee (size and composition at their discretion).

Implicit in the review process is the right of the committee to refuse acceptance. Authors of rejected abstracts can make changes and re-submit, if they can do so within the time limit established for receipt of abstracts.

- c. Ted Bornhorst suggested that the Board look into desktop publishing of peer-reviewed, expanded abstracts and short papers. This would allow authors who might not normally publish in established journals to semi-formally publish their research. The idea was tabled for future discussion.
- d. A suggestion was made by Ted Bornhorst to create an ILSG newsletter that would be published early in the calendar year. It would serve to publicize upcoming ILSG meetings and other events, as well as highlight exploration and research activities. The concept was generally approved. Ted will prepare a mock-up in the following months with a student assistant. Board members will continue to discuss and track the progress of the venture.
- e. Board agreed to have a formal meeting at the IGCP Conference, August 25-27, 1995.

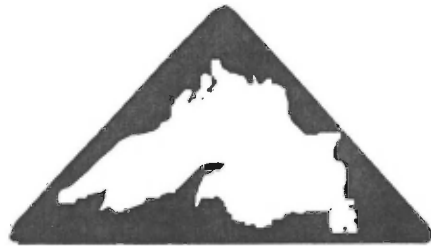
Budgeting for the 41st ILSG was designed to keep registration costs at a minimum in order to help attract potential delegates to Marathon despite prohibitively long travel distances. Fees were largely set on a cost-recovery basis. Many of the duties and services which could normally be contracted out to other agencies (e.g., university extension services) were taken care of by OGS staff in order to reduce costs. Field trip guidebooks were also sold at just above cost to attendees. Since the meeting, the guidebooks have been reprinted several times; sales in Thunder Bay continue to be brisk, especially during field season.

The final financial analysis appears to indicate that the 41st ILSG managed to turn a modest profit. This is, in itself, especially rewarding, considering our 'user-friendly' pricing practices, unforeseen print-run problems and losses in Canada-US exchange

rates. Mark O'Brien, local Secretary-Treasurer, is to be commended for his role in keeping us on an even financial keel.

I have received many favourable comments and kudos on the organization of the 41st ILSG. Despite many 'arms-length' logistical problems, uncooperative (but typical) north shore weather and minor glitches, it proved to be a very successful meeting. I must again thank all the people in Thunder Bay and Marathon who helped to pull it off. Special thanks must also go out to all the field trip leaders for their perseverance. Cliff Shaw graciously filled in on the alkaline rocks trip for Dave Watkinson, who was unfortunately ill. Former chairmen, Ron Sage, Ted Bornhorst, Manfred Kehlenbeck and Ed Frey provided invaluable organizational advice. Lastly, I would like to acknowledge all those who made the effort to come to Marathon and who continue to support the Institute on Lake Superior Geology.

Mark Smyk
Chairman, 41st ILSG
Thunder Bay, Ontario



PROGRAM

CALENDAR OF EVENTS AND PROGRAM

WEDNESDAY, MAY 15

8:00 AM - 6:00 PM FIELD TRIPS 1 AND 2

1. *GLACIAL GEOLOGY OF WESTERN WISCONSIN*

Leader: Mark D. Johnson (Gustavus Adolphus College)

2. *GEOLOGY OF THE MONTREAL RIVER MONOCLINE:*

A TRAVERSE THROUGH 25 KM OF THE CRUST

Leader: William F. Cannon (U. S. Geological Survey)

5:00 PM - 8:00 PM REGISTRATION

7:00 PM - 10:00 PM ICEBREAKER AND POSTER SESSION (Cash Bar)

(Authors present at posters 7:30 PM - 9:00 PM)

THURSDAY, MAY 16

 NOTE : TECHNICAL SESSIONS ARE IN THE NAMEKAGON ROOM, TELEMAR LODGE
* STUDENT PRESENTATION

8:00 AM REGISTRATION CONTINUES

TECHNICAL SESSION I

SESSION CHAIRS: KLAUS SCHULZ AND GLEN ADAMS

8:55 AM OPENING - 42ND ANNUAL INSTITUTE ON LAKE SUPERIOR GEOLOGY
L. G. Woodruff, General Chair

✓ 9:00 AM KEYNOTE ADDRESS

Miller, J. D., Jr., and Vervoort, J. D.

*The Latent Magmatic Stage of the Midcontinent Rift: A Period of Magmatic
Underplating and Melting of the Lower Crust*

✓ 9:30 AM Bornhorst, T. J., and Dolan, M. T.

An Electronic Component of the Institute on Lake Superior Geology

✓ 9:50 AM PRESENTATION OF PROPOSED CHANGES TO THE I.L.S.G. CONSTITUTION

10:00 AM COFFEE BREAK AND POSTER SESSION

- 10:20 AM Ames, D. E., Jonasson, I. R., Parrish, R. R., Watkinson, D. H., and Gibson, H. L.
Regional Hydrothermal Massive Sulphide Producing System and U/Pb Hydrothermal Titanite Age Constraints, Onaping Formation, Sudbury Structure, Ontario
- 10:40 AM Ripley, E. M.
Petrogenetic Relationships between Apatite-Bearing and Apatite-Deficient Iron Oxide-Rich Intrusions and Massive Sulfide Mineralization in the Duluth Complex, MN
- 11:00 AM *Peterson, D. M.
Targeting Footwall Copper-PGE Deposits in the Duluth Complex Based on Sudbury Mining Camp Analogs
- 11:20 AM Saini-Eidukat, B., Rudashevsky, N. S., and Polozov, A. G.
Occurrence of Hibbingite in the Duluth Complex, Minnesota, and in the Noril'sk Complex and Korshunovskoe Iron Ore Deposit, Russia
- 11:40 AM Mudrey, M. G., Jr., Brown, B. A., Freiberg, P. G., and Simo, J. A.
Mississippi Valley-Type Mineralization in the Fox River Valley, Eastern Wisconsin
- 12:00 PM **LUNCH BREAK**

TECHNICAL SESSION II
SESSION CHAIRS: ED RIPLEY AND MARK SMYK

- ✓ 2:00 PM Boerboom, T. J.
Southward Extension of the Penokean Terrane through Stearns County, Central Minnesota
- ? 2:20 PM *Darrah, K. S., Holm, D. K., Dahl, P. S., and Lux, D. R.
Petrographic and Thermobarometric Analysis of the Metamorphosed Little Falls Formation, Central Minnesota, with Implications for Early Proterozoic Tectonism
- ✓ 2:40 PM Holm, D. K., Dahl, P. S., and Lux, D. R.
Was Lithospheric Delamination an Important Process in the Evolution of Early Proterozoic Collisional Orogens?
- 3:00 PM **COFFEE BREAK AND POSTER SESSION**
- 3:20 PM Schmidt, S. Th., and Stern, W.
Clay Minerals of the North Shore Volcanic Group and Possible Relationship to Copper Precipitation during Alteration

3:40 PM *Bekker, A., and Karhu, J. A.
*Study of Carbon Isotope Ratios in Carbonates of the Early Proterozoic Snowy
Pass Supergroup, WY and Its Application for Correlation with the Chocoday
Group, MI and the Huronian Supergroup, ON*

4:00 PM Larsen, C.
Late Holocene Lake Superior -- Isostatic and Climactic Lake-Level Change

4:20 PM Uchytel, S. J., Steffensen, C. K., Jarvie, D. M., Dickas, A. B.,
and Mudrey, M. G., Jr.
*Outcrop and Subsurface Core Analysis and Relationship to Regional
Hydrocarbon Prospectiveness of the Middle Proterozoic Nonesuch Formation
Northern Wisconsin and Michigan*

6:30 PM - 7:30 PM **MIXER - CASH BAR**

7:30 PM - 9:30 PM **ANNUAL BANQUET & AWARDS PRESENTATION**
Announcement of the 43rd Annual Meeting location.
1996 Goldich Award presentation to Dr. David Southwick,
Minnesota Geological Survey, by Dr. G. B. Morey.
Banquet speaker: Dr. Stephen E. Kesler, University of Michigan,
Ann Arbor, Michigan:
SUSTAINABLE MINERAL DEVELOPMENT -- FACT OR FICTION?

FRIDAY, MAY 17

8:30 AM REGISTRATION CONTINUES

TECHNICAL SESSION III SESSION CHAIRS: SIDNEY HEMMING AND TERRY BOERBOOM

9:00 AM Chandler, V. W.
*The West-Central Minnesota Earthquake of June 5, 1993: An Opportunity to
Re-examine Seismicity near the Morris Fault*

9:20 AM *Wilson, S. M., and Klasner, J. S.
*A Structural and Kinematic Analysis of the McCaslin Formation near McCaslin
Mountain, Wisconsin*

9:40 AM Westjohn, D. B.
*Regional Finite Strain Patterns in Proterozoic Slates and Quartzites:
Implications for Heterogeneous Strain Related to Flexural Slip Folding in the
Marquette Synclinorium*

10:00 AM **COFFEE BREAK AND POSTER SESSION**

- 10:30 AM *Adamson, K. F.
Petrology, Stratigraphy, and Sedimentation of the Middle Proterozoic Bayfield Group of Northwestern Wisconsin
- 10:50 AM Ojakangas, R. W.
Tidalites of Early Proterozoic Age in the Western Lake Superior Region: Minnesota, Wisconsin and Michigan
- 11:10 AM Ojakangas, G. W.
Cyclic Tidal Laminations in the Early Proterozoic Pokegama Formation: Digital Image Analysis and Computer Modeling
- 11:30 AM **LUNCH BREAK ☞ NOTE: ALL POSTERS MUST BE REMOVED**

TECHNICAL SESSION IV
SESSION CHAIRS: MARK JIRSA AND RON SAGE

- 1:30 PM Hemming, S. R., McLennan, S. M., and Hanson, G. N.
Geochemical Source Characteristics and Diagenetic Trends of the Virginia Formation, Mesabi Iron Range, Minnesota
- 1:50 PM Medaris, L. G., Jr., Dott, R. H., Jr., Fournelle, J. H., Johnson, C. M., Schott, R. C., and Baumgartner, L. P.
Age and Geological Significance of the Baraboo Quartzite
- 2:10 PM Jirsa, M. A.
Genesis of a Timiskaming-Like Sequence in the Southern Wawa Subprovince, Northeastern Minnesota
- 2:30 PM Smyk, M. C. and Kingston, D. M.
Basaltic Komatiites and Associated Rocks: Implications on the Nature of Volcanism in Part of the Schreiber-Hemlo Greenstone Belt, Northwestern Ontario
- 2:50 PM **PRESENTATION OF STUDENT PAPER AWARDS**
- 3:00 PM **CLOSING REMARKS**
- 3:10 PM **COFFEE BREAK**
- 3:30 PM Gene LaBerge
Discussion of Logistical Details for the Flambeau Mine Field Trip Minerals of the Flambeau Mine (no abstract)
- 4:00 PM **SESSION ENDS**

SATURDAY, MAY 18

7:00 AM - 6:00 PM FIELD TRIP 3

3. TOUR OF FLAMBEAU COPPER-GOLD MINE

Leaders: Gene L. LaBerge (University of Wisconsin-Oshkosh)
and Staff Geologists, Flambeau Mine

SUNDAY, MAY 19

8:00 AM - 5:00 PM FIELD TRIPS 4 AND 5

4. EARLY TO MIDDLE PROTEROZOIC GEOLOGY OF THE LAKE NAMEKAGON REGION

Leaders: William F. Cannon, Laurel G. Woodruff, and
Suzanne W. Nicholson (U. S. Geological Survey)

5. LAKE NAMEKAGON AND PENOKEE GAP AREAS, WEST GOGEBIC RANGE, WISCONSIN

Leaders: John S. Klasner (Western Illinois University) and
Gene L. LaBerge (University of Wisconsin-Oshkosh)

POSTER SESSION

SESSION CHAIR: SUZANNE NICHOLSON

7:30 PM WEDNESDAY, MAY 15, TO NOON FRIDAY, MAY 17

Cannon, W. F., and Kress, T. H.

New Digital Geologic Map of Minnesota, Wisconsin, and Upper Michigan
(no abstract)

Cannon, W. F., Nicholson, S. W., Woodruff, L. G., Hedgman, C. A., and Schulz, K. J.
Geologic Map of the Ontonagon and part of the Wakefield 30' x 60' Quadrangles, Michigan
(no abstract)

Gere, M. A., Jr.

Michigan Mineral Lease Exploration Data Inventory

Johnson, A. M., and Gere, M. A., Jr.

*Identifying Geologic and Other Potential Resources from Michigan's Abandoned Underground
Mine Inventory*

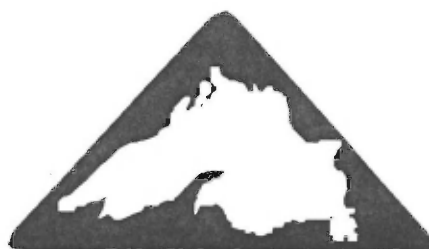
Kalliokoski, J.

An Ancient Landslide at "Red Rocks", Keweenaw Bay, Michigan

✓ Kucks, R. P., and Horton, R. J.

Aeromagnetic Map of Lake Superior

- Morey, G. B., and Cleland, J. M.
Preliminary Sedimentologic and Petrologic Analysis of the Early Proterozoic Mahnomen Formation (North Range Group) East-Central Minnesota
- *Naiman, Z., Wirth, K. R., Morey, G. B., and Miller, J. D.
Metamorphism of Chengwatana Volcanic Group near Taylors Falls and from Osseo Core
- *Neilson, K. Stendahl, R., Kropf, E., and Craddock, J. P.
A Continuum of Stress-Strain Fields (2.0-1.0 Ga) along the Northern Margin of the Keweenaw Province, Ontario, Canada
- Sage, R. P., Morris, T. F., Crabtree, D., Murray, C. A., Bennett, G., Hailstone, M.,
 Nicholson, T., Painosi, S., and Josey, S.
Ultramafic Dike with Mantle Xenoliths: Implications to Diamond Exploration in Wawa
- Spector, A., and Lawler, T. L.
Northeastern Minnesota Duluth Complex Mineral Potential
- Swenor, W. T.
Update on the Geological Core and Sample Repository
- Wattrus, N. J., Anderson, K., Sharkey, J., and Holcombe, T.
A New Bathymetric Map of Lake Superior
- Wirth, K. R., Naiman, Z., Vervoort, J. D., Miller, J. D., and Morey, G. B.
Geochemistry of Chengwatana Volcanic Group near Taylors Falls and from Osseo Core



ABSTRACTS

PETROLOGY, STRATIGRAPHY, AND SEDIMENTATION OF THE MIDDLE PROTEROZOIC BAYFIELD GROUP OF NORTHWESTERN WISCONSIN.

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Petrographic and field evidence suggest that the Bayfield Group units, the lithofeldspathic Orienta Formation and the lithofeldspathic Chequamegon Formation, are the same unit beneath the quartzose Devils Island Formation. Previous stratigraphic studies place the three units in the following order, from the bottom up: Orienta, Devils Island and Chequamegon (Thwaites, 1912; Myers, 1971). The contact between the Devils Island Formation and Chequamegon Formation is not present on Devils Island as previous studies suggest. This stratigraphy would better match the probable correlative units some tens of miles to the west in east-central Minnesota, the lithofeldspathic Fond du Lac Formation and the overlying quartzose Hinckley Sandstone.

The Orienta and Chequamegon Formations both appear to have been formed by fluvial processes while the Devils Island Formation is more indicative of a shallow standing body of water (Ojakangas & Morey, 1982; Morey & Ojakangas, 1982). Supporting evidence includes a northeasterly paleocurrent direction trend for both the Orienta and Chequamegon Formations. The Devils Island Formation has a less prominent northeasterly paleocurrent trend along with many divergent paleocurrent directions.

Preliminary petrographic data from the Devils Island Formation show that nearly 100% of the primary framework grains are quartz. The primary framework grains of the Orienta Formation are 45 to 65% quartz, 35 to 50% feldspar, and 0 to 10% rock fragments (volcanic and granitic). The Chequamegon Formation is very similar to the Orienta Formation, generally consisting of 45 to 65% quartz, 30 to 50% feldspar, and 5 to 10% rock fragments.

References

- Morey, G. B., and R. W. Ojakangas, 1982, Keweenawan sedimentary rocks of eastern Minnesota and northwestern Wisconsin, in Wold R. J. and W. J. Hinze, eds., *Geology and tectonics of the Lake Superior basin: GSA Memoir 156*, p. 135-146.
- Myers, W. D., 1971, *The sedimentology and tectonic significance of the Bayfield Group (upper Keweenawan?) Wisconsin and Minnesota: Unpublished Ph.D. dissertation, University of Wisconsin, Madison, Wisconsin, 269 p.*
- Ojakangas, R. W., and G. B. Morey, 1982, Keweenawan sedimentary rocks of the Lake Superior region: a summary, in Wold R. J. and W. J. Hinze, eds., *Geology and tectonics of the Lake Superior basin: GSA Memoir 156*, p. 157-164.
- Thwaites, F. T., 1912, Sandstones of the Wisconsin coast of Lake Superior: *Wisconsin Geological and Natural History Bulletin* 25, 117p.

REGIONAL HYDROTHERMAL MASSIVE SULPHIDE PRODUCING SYSTEM AND U/PB HYDROTHERMAL TITANITE AGE CONSTRAINTS, ONAPING FORMATION, SUDBURY STRUCTURE, ONTARIO.

Ames, D.E.*, Jonasson, I.R., Parrish, R.R. Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, K1A 0E8; Watkinson, D.H. Ottawa-Carleton Geoscience Centre, Department of Earth Sciences, Carleton University, Ottawa, Ontario, K1S 5B6; Gibson, H.L., Geology Department, Laurentian University, Sudbury, Ontario, P3E 2C6.

The objectives of the present study in the Onaping Formation, Sudbury Structure are to determine: 1) the stratigraphic and structural controls on alteration, 2) the spatial distribution, mineralogy, mineral-chemical characteristics, timing, and origin of alteration types and, 3) the relationship between regional scale hydrothermal alteration with intra-Onaping base metal occurrences and to the overlying Zn-Cu-Pb Errington and Vermilion massive sulphide deposits. Research is based on 1:2000 scale mapping carried out during three field seasons, of ten transects up to 6 km width across the Onaping Formation, distributed around the circumference of the structural basin.

The Paleoproterozoic Onaping Formation forms the base of the Whitewater Group, Sudbury Structure and is the footwall sequence to the 8.7 Mt Errington and Vermilion VMS deposits. Comprehensive field evidence indicates that this 1400m thick fragmental succession is hydrothermally altered pyroclastic-like fall and flow, debris-flow deposits and hydroclastic breccia (Ames and Gibson, 1995). Syndepositional radial and minor concentric faults partially control emplacement of the lower part of the Onaping Formation and are conduits for alkali metasomatic fluids. Evidence for a regional subseafloor hydrothermal system includes vertically stacked, "basin-wide" semiconformable alteration zones consisting of, from base to top, silicification, albitization, chloritization, carbonatization and feldspathization. The latter includes microcline, hyalophane and celsian. The syndepositional basal zone of silicification consists of an earlier phase of K-feldspar overprinted by albite and quartz with minor epidote. These events are also mimicked in the overlying, locally discordant, zones of syndepositional albitization. Chlorite although dominant in the Contact units is present throughout the Onaping Formation as pycnochlorite-ripidolite except near base-metal occurrences and deposits and the basal silicification zone where more Mg-rich varieties are present. A late stage of high Fe-ripidolite is associated with pyrrhotite-chalcopyrite-siderite in the base-metal deposits and occurrences. Proximal alteration to base metal deposits includes, barian muscovite, hyalophane, celsian, quartz, carbon, ankerite, dolomite and late siderite. Regional carbonatization, consists of calcite, and is pervasive in the upper 1 km except around base metal showings and local zones of lower temperature silicification. The upper zone of feldspathization contains low-temperature k-feldspar with minor albite which is overprinted by celsian, reflecting low-temperature seawater-rock reactions in the shallow subseafloor.

Amphibole veins with albitized haloes represent one of the youngest hydrothermal events in the Onaping Formation; they crosscut igneous -textured intrusions cogenetic with the fragmental andesitic Onaping Formation. Conventional U/Pb geochronology of hydrothermal titanite within the metasomatized haloes of the amphibole veins yields an age circa 1850 Ma. One of the world's most extensive hydrothermal circulation systems developed in the Onaping breccias due to heat loss from the 1850 Ma Sudbury Intrusive Complex and coeval sublayer rocks. This new U/Pb titanite age on late-stage hydrothermal alteration proves that the complex Sudbury event was complete within error of geochronological dating.

The mechanisms of brecciation and emplacement of the Onaping Formation are similar to some volcanic deposits however, it is not a typical, volcanic cauldron sequence or fallback breccia. The Onaping Formation represents a dominantly subaqueously deposited impact melt based on the epsilon Nd crustal signature between -7.6 to -10.3, the lack of phenocrysts in explosive ash flow-like deposits suggesting little crustal residence time, the presence of abundant shock metamorphic features including shocked zircons and cusped, platy and blocky microvesicular shard morphologies. Emplacement of the SIC and sublayer provided the heat required to initiate fluid circulation in the 1.4 km thick fragmental sequence and led to the development of a short-lived hydrothermal system that produced the overlying Zn-Cu-Pb replacement deposits hosted in carbonate sinter mounds. The

exceptional preservation of the fragmental strata and one of the world's most extensive semi-conformable alteration systems, permits detailed investigation of processes involved in generating Paleoproterozoic massive sulphide deposits, the role of hydrothermal processes in large scale meteorite impact structures and the emplacement mechanisms for large impact crater-fill deposits.

Ames, D.E. and Gibson, H.L. 1995: Controls on and geological setting of regional hydrothermal alteration within the Onaping Formation, footwall to the Errington and Vermilion base metal deposits, Sudbury Structure, Ontario; in Current Research 1995-E; Geological Survey of Canada, 161-173.

STUDY OF CARBON ISOTOPE RATIOS IN CARBONATES OF THE EARLY PROTEROZOIC SNOWY PASS SUPERGROUP, WY AND ITS APPLICATION FOR CORRELATION WITH THE CHOCOLAY GROUP, MI AND THE HURONIAN SUPERGROUP, ON.

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Carbon has a relatively long residence time in the oceans relative to the mixing time of sea water, thus making marine waters nearly homogenous in respect to carbon isotope composition. As such, carbon isotope ratio changes can be used for stratigraphic correlations between carbonate units deposited in open basins. In addition, carbonates are usually considered to retain their original carbon isotope signatures nearly unchanged in diagenetic and even in metamorphic alterations. In this study, analyses of carbon isotope ratios from the Vagner Formation, the Lookout Schist, and the Nash Fork Formation were carried out. We compare our results with available data from the Huronian and Marquette Range Supergroups, and other sequences worldwide to put some constraints on the time of deposition, and to draw a correlation between these sequences. Our results also have implication for understanding of the carbon cycle in Early Proterozoic time.

The Snowy Pass Supergroup, Wyoming, consists of the Deep Lake (DLG) and the Libby Creek (LCG) Groups. The DLG and the lower LCG were deposited between 2.45 and 2.1 Ga (Premo and Van Schmus, 1989) and are overlain by the allochthonous upper LCG. The upper DLG and the lower LCG exhibit three-large scale cycles with tillites at the base and sandstones above (Campbell Lake Fm. → Cascade Fm., Vagner Fm. → Rock Knoll Fm., Headquarters Fm. → Heart Fm. and Medicine Peak Quartzite). Limestones of the Vagner Formation were deposited following glacial retreat; they exhibit fine laminations and interlayering with siltstone. The Lookout Schist of the lower LCG locally includes thin layers of brown impure dolomite. The Nash Fork Formation is a thick (>2 km) sequence of siliceous cross-bedded dolomites with flat-pebble conglomerates, pseudomorphs after gypsum, and stromatolite bioherms, enclosed by black phyllites with graphite and pyrite, indicating a reducing environment. To that end, intertidal and subtidal environments of deposition were suggested for this unit (Houston and Karlstrom, 1992). Greenschist metamorphic facies dominate in all units, but the grade increases to the lower amphibolite facies to the NE.

Fourteen samples from the Vagner Fm. were analyzed for carbon and oxygen isotope ratios. Each sample exhibits a negative carbon isotope values with an average of $\delta^{13}\text{C} = -2.1\text{‰}$. Data comparison with the correlative Bruce Member of the Espanola Formation, (Huronian Supergroup) reported by Veizer et al. (1992) reveals a strong resemblance (Fig. 1), which supports their correlation. Regarding the low $\delta^{18}\text{O}$ values (average for the Vagner Fm.: $\delta^{18}\text{O} = -18.7\text{‰}$, PDB) we follow the suggestion of Veizer et al. (1992) that the lower values may be due to meteoric water flux.

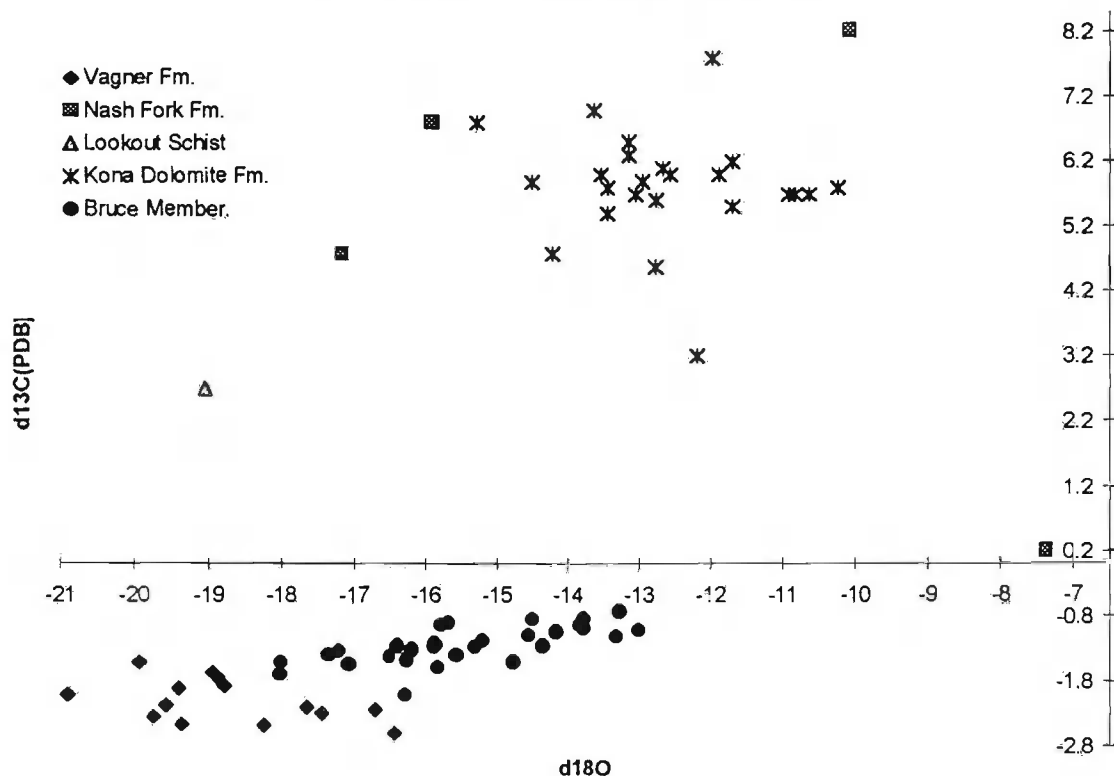
Only one sample was analyzed from the Lookout Schist; it showed $\delta^{13}\text{C} = 2.7\text{‰}$, $\delta^{18}\text{O} = -19.05\text{‰}$, PDB. The $\delta^{13}\text{C}$ is intermediate between the low $\delta^{13}\text{C}$ values measured from the underlying Vagner Formation and the high values of the overlying Nash Fork Fm. These data seem to indicate a significant positive shift in the isotopic composition of the marine carbonates.

Four samples were analyzed from the Nash Fork Formation. All except one exhibit high positive carbon isotope ratios (average: $\delta^{13}\text{C} = 5\text{‰}$, highest: $\delta^{13}\text{C} = 8.23\text{‰}$). These carbon isotope ratios resemble values of the Kona Dolomite (Fig. 1), Fennoscandian carbonates, and other carbonates of about the same age worldwide (see Karhu, 1993). Based on Sm-Nd and U-Pb dating of sequences in which this excursion occurs in Fennoscandia, it is bracketed between 2.21 and 2.06 Ga. Correlation of the Kona Dolomite and the Nash Fork Formation with these better geochemically studied and dated units on the basis of carbon isotope ratios suggests a similar time of deposition. It should be noted, however, that one sample from the Nash Fork Formation has a "low" carbon isotope ratio in comparison with the general trend. In addition, both the Kona Dolomite and the Nash Fork Formation have somewhat lower values than the 2.2 - 2.1 Ga Fennoscandian carbonates ($\delta^{13}\text{C} = 10 \pm 3\text{‰}$; Karhu, 1993).

Roscoe and Card (1993) correlated the DLG and the lower LCG with the Huronian Supergroup, and the upper LCG with the Marquette Range Supergroup on the bases of stratigraphic, sedimentological, and age similarities. Our data support their correlation and demonstrate the applicability of chemostratigraphy as a tool in the correlation of Early Proterozoic carbonates from different basins.

Our data confirm the worldwide character of the aforementioned carbon isotope excursion. This carbon isotope excursion indicates a high rate of burial of organic matter, leading to increased atmospheric oxygen level. This increase in oxygen level was suggested between 2.2-1.9 Ga based on independent geological data (Holland and Beukes, 1990). Iron formations were deposited after the deposition of the ^{13}C -enriched carbonates in MI, WY, and Fennoscandia. This indicates that deep oceans remained anoxic even after the excursion, while dissolved iron was transported and precipitated in the shallow shelf areas. The high positive excursion in carbon isotope ratio might be correlated with rifting, formation of anoxic basins and carbonate platforms, high biomass fertility, high sedimentation rate and many other factors. More detailed work is necessary before a working model can be developed.

Fig.1. Scatter diagram of $\delta^{18}\text{O}$ vs. $\delta^{13}\text{C}$ for studied Early Proterozoic carbonates. Data for the Kona Dolomite from Feng (1986) and for the Bruce Member from Veizer et al. (1992).



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SOUTHWARD EXTENSION OF THE PENOKEAN TERRANE THROUGH STEARNS COUNTY, CENTRAL MINNESOTA

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Recent remapping by the Minnesota Geological Survey¹ of the Precambrian bedrock geology of Stearns County has identified a previously unrecognized southwestern extension of the Penokean Orogen (Fig. 1). Prior to this study, most of Stearns County was considered to be underlain by Archean high-grade granitoid gneisses, with the exception of some Penokean intrusions in the southeastern part of the county. Although the northwestern part of the county is still interpreted to be Archean gneiss, it is now recognized that Early Proterozoic rocks, which include supracrustal rocks of the Mille Lacs Group and Little Falls Formation, as well as many intrusions of varied size and composition, are predominant. In addition, thrust and strike- or dip-slip faults are an important aspect of the geology in this region. Because most of Stearns County is covered by glacial drift and patches of Cretaceous rocks, drill-hole and geophysical data were utilized extensively to infer the structural and lithologic attributes of the bedrock.

The revised geology can be subdivided into the following six broad lithologic units, listed from oldest to youngest: (1) Archean granitoid gneisses; (2) the Archean or Early Proterozoic, granulite-grade Sartell Gneiss (broadly grouped with the Hillman Migmatite outside of Stearns County); (3) the Early Proterozoic Mille Lacs Group; (4) the Early Proterozoic Little Falls Formation; (5) Animikie strata of the Long Prairie basin; and (6) Early Proterozoic intrusions that intrude most of the above.

Archean granitoid gneiss at the northwest corner of the county is foliated and variably lineated along a northeast trend and locally pervasively altered to epidote. The Sartell Gneiss contains the metamorphic minerals orthopyroxene, garnet, sillimanite, and local hercynite and corundum, and includes some granitoid gneiss.

The Mille Lacs Group underlies the southwest corner of the county in a block wedged between older Archean basement rocks. This group of rocks is conjectured to consist of metamorphosed volcanic and sedimentary rocks and thin beds of iron-formation. Thrust faults are indicated by geophysical data to occur both within and marginal to the Mille Lacs Group.

The Little Falls Formation contains a sillimanite-garnet-staurolite assemblage that typifies this unit to the north. The western edge of the Little Falls Formation has been thrust over the Mille Lacs Group.

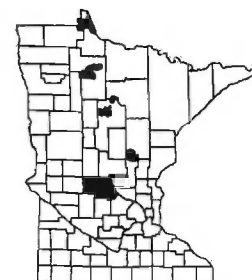
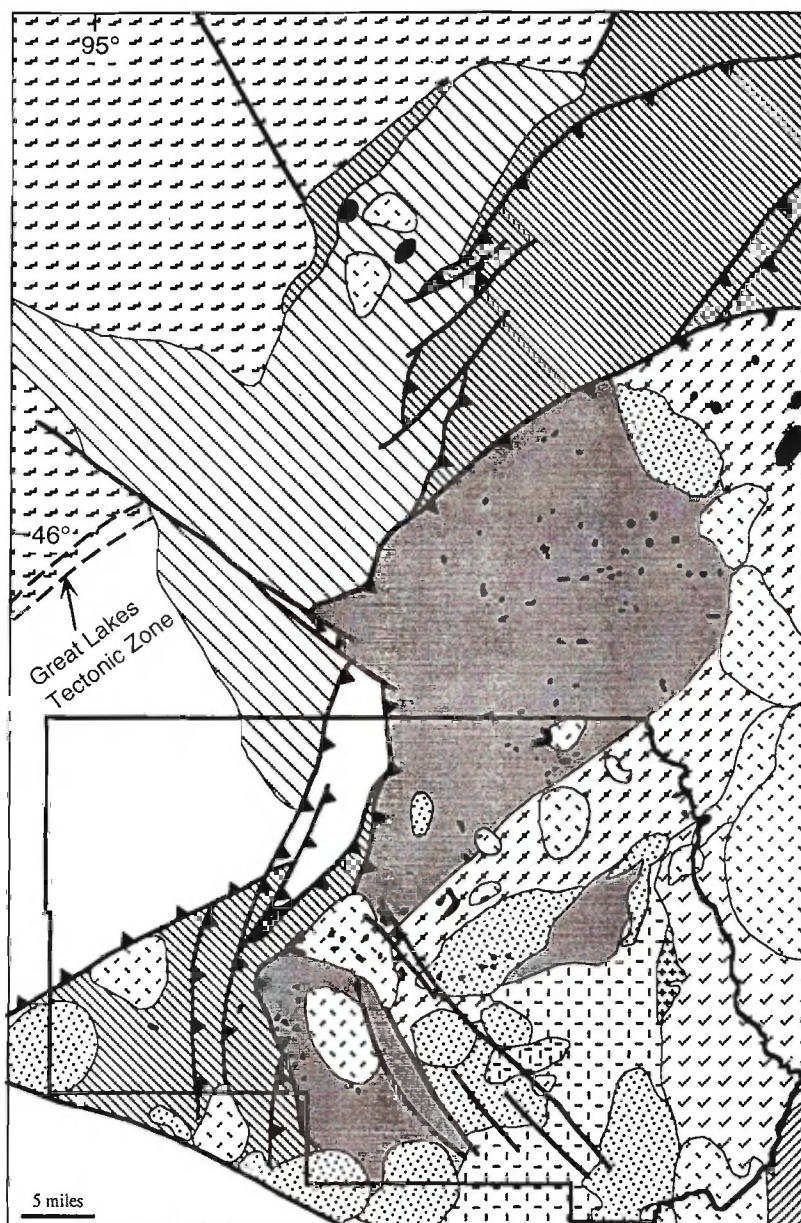
The Long Prairie basin forms an outlier of Animikie strata that correlates with, but is physically separated from, the Virginia Formation to the northwest. The strata are only weakly deformed relative to other Early Proterozoic supracrustal rocks, but deformation is strongest along its southeastern edge, where it has been overthrust by older rocks of the Penokean Orogen.

The intrusive rocks range widely in size and composition from small ultramafic plugs, irregularly shaped mafic charnockitic bodies, large plutons of gabbroic to granitoid rocks, to thin cross-cutting dikes of diabase and porphyritic granite. Most or all of these intrusions are inferred to be late- to post-kinematic with regard to the Penokean orogeny. They occur not only as discrete bodies in the supracrustal rocks but, in the southeast part of the county, as a continuous plutonic terrane of dominantly granitoid bodies that include the Richmond Granite, Rockville Granite, St. Cloud (Red) Granite, and the Reformatory granodiorite. Earlier workers established Early Proterozoic ages for these granitoid rocks and diabase dikes, but modern geochronologic data are lacking. These plutonic rocks are so well exposed in this part of the county that local remapping on airphotos at a scale of 1:2400 was possible.

Several gross structural attributes have been recognized from geophysical data. The wedge of Mille Lacs Group strata is bounded on its northwest side by a steep northwest dipping fault interpreted to be an Archean structure reactivated during the Penokean orogeny. On its southwest side the wedge is bounded by a brittle tear fault that has juxtaposed the Penokean strata against older Archean rocks over some 50 km length and produced a major offset of the Penokean margin. Although supracrustal rocks of the Penokean Orogen terminate against this fault, evidence suggests that the Penokean Rockville Granite extends across but may be affected by it. The fault has also acted as a locus of emplacement for other smaller Penokean plutons. Other north-striking, southeast-dipping thrust faults have imbricated the Mille Lacs Group strata; they also occur beneath the overriding Little Falls Formation. These southeast-dipping thrust faults are consistent with previously mapped faults in Penokean strata to the north. The east-curving morphology of the thrusts within the Penokean Orogen near the Archean block to the northwest imply that the latter may have acted as an buttress that deflected deformation.

The most important findings of the newly interpreted bedrock geology of Stearns County are the recognition that the Mille Lacs Group and Little Falls Formation within the Penokean terrane extend considerably farther south than previously recognized, that a tear fault has substantially offset the Penokean margin and juxtaposed the Penokean terrane against older Archean rocks, and that thrust faults have played a significant role in the structural evolution of this area. The size, distribution, and abundance of Penokean intrusive rocks are also better recognized and understood.

¹This interpretation was completed as part of the Stearns county geologic atlas (Minnesota Geological Survey, County Atlas Series Atlas C-10, Part A), which includes data base, bedrock geology, surficial geology, Quaternary stratigraphy, depth to bedrock, bedrock topography, and mineral resources plates.



Location of
Stearns County

Partial funding for the Stearns County Atlas was approved by the Minnesota Legislature (M.L. 91, Ch. 254, Art. 1, Sec. 14, Subd. 4[F], and M.L. 93, Ch. 172, Sec. 14, Subd. 11[g]) as recommended by the Legislative Commission on Minnesota Resources from the Minnesota Environment and Natural Resources Trust Fund.

EXPLANATION

EARLY PROTEROZOIC ROCKS

- Mafic to ultramafic plutons; includes peridotite, gabbro, and gabbro.
- Gabbro, norite, charnockite; includes granites with charnockitic affinities.
- Granitoid plutons, undivided
- St. Cloud (Red) Granite
- Richmond Granite
- Rockville Granite
- Reformatory Granodiorite
- Long Prairie basin (Animikie Basin, argillite and graywacke).

- Little Falls Formation (staurolite schist).
- Mille Lacs Group, undivided.
- Miscellaneous metamorphosed volcanic and sedimentary rocks.

ARCHEAN ROCKS

- Sartell Gneiss and Hillman Migmatite (may be Early Proterozoic).
- Granite-greenstone terrane.
- High-grade gneiss terrane.

- Strike-slip or dip-slip fault.
- Thrust fault.
- Lithologic contact.

Figure 1. Simplified pre-Cretaceous geologic map of central Minnesota. Stearns County is outlined.

AN ELECTRONIC COMPONENT OF THE INSTITUTE ON LAKE SUPERIOR GEOLOGY

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The information superhighway is becoming an increasingly important part of daily professional activities. Electronic communication can help the Institute on Lake Superior Geology better serve its constituents, perhaps attract new professionals to participate in the organization, and make the ILSG better known beyond the bounds of the Great Lakes region. The Board of Directors of the Institute on Lake Superior Geology has authorized the creation of an ILSG home page. The current plan is for the home page to contain the sort of information found in the introductory pages of the proceedings volume. The information will include future meeting locations, past meeting locations, list of awards given, Board of Directors, and who to contact. This WEB resource could also include lists of titles of abstracts, lists of available field guidebooks, list of members, links to other sites of interest, etc. Suggestions are welcomed. The ILSG home page is in construction and will contain considerable information by early September, 1996. The URL will be http://www.geo.mtu.edu/great_lakes/ilsg/

Discussion groups now exist in many areas of professional interest. Participants in these lists can ask questions of or make comments to other members of the list. Members of the list will automatically receive email through the list server. A Lake Superior Geology list will be maintained by the senior author through Michigan Tech. The Board of Directors of the Institute on Lake Superior Geology encouraged creation of this list. For more information on the Lake Superior Geology discussion list, email the list server at Michigan Tech:

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THE WEST-CENTRAL MINNESOTA EARTHQUAKE OF JUNE 5, 1993: AN OPPORTUNITY TO RE-EXAMINE SEISMICITY NEAR THE MORRIS FAULT

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The June 5, 1993, west-central Minnesota earthquake (mbLg=4.1) provides an opportunity to re-investigate Minnesota seismicity and its possible relationship to reactivated basement structures. The earthquake occurred within 25 kilometers of the much larger July 7, 1975, west-central Minnesota earthquake (mbLg=4.6), which has been attributed to the Morris fault, a northeast-striking crustal discontinuity separating two distinct Archean terranes. Intensity data from the 1993 earthquake confirm the position of the instrumentally determined epicenter and reveal a felt area of about 69,500 square kilometers, with a maximum intensity of V. Some local perturbations in the isoseisms correlate with features in the Precambrian bedrock, implying that seismic energy may be focused significantly by crustal structure. Focal depth estimates based on intensity data imply that the 1993 focal depth is similar to that of the 1975 earthquake, which has been independently estimated to be 7.5 kilometers.

The Morris fault has been generally thought to be the major seismogenic feature in the region, but neither the 1993 hypocenter inferred by this study nor the 1975 hypocenter agree with the subsurface trace of the fault as revealed by seismic-reflection data and magnetic modeling. Alternative sources for the 1975 and 1993 earthquakes include west-northwest-striking sub-vertical structures that are interpreted to consist chiefly of mafic dikes and related fractures. Some of these fractures are associated with minor faulting—as evidenced by small offsets in the Morris fault—and possible disruption of Cretaceous strata. Neither the Morris fault nor the west-northwest structures agree with a loosely constrained focal mechanism for the 1975 earthquake, but the west-northwest structures are favorably oriented to be reactivated by the east-northeast regional compression that has been averaged for the eastern United States.

This study indicates that minor basement structures, such as mafic dikes and associated fractures, may play a largely unappreciated role in seismicity of mid-continental regions. Such structures may not be evident in many existing geological and geophysical data sets.

This study was supported by the University of Minnesota through the State Special Appropriation of the Minnesota Legislature.

Petrographic and thermobarometric analysis of the metamorphosed Little Falls Formation, central Minnesota, with implications for Early Proterozoic tectonism

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Recent advances in thermobarometry have significantly increased our understanding of regional metamorphism in ancient orogenic belts, allowing important constraints to be made on their tectono-thermal evolution. However, there have been few quantitative studies of the pressure and temperature evolution of rocks metamorphosed during the Early Proterozoic (1870-1820 Ma) Penokean orogeny in Minnesota. One previous study in east-central Minnesota suggests that Early Proterozoic sedimentary rocks metamorphosed during the Penokean orogeny reached temperatures of 450-600°C and minimum pressures of 5-6 kbar (Holm and Selverstone, 1990).

The Early Proterozoic Little Falls Formation (LFF), located within the internal zone of the Penokean orogenic belt, is a biotite-quartz-plagioclase-muscovite schist whose protolith was a shale and graywacke sequence with carbonate concretions. Metamorphic grade increases from garnet grade in the north to staurolite grade in the south. One drill core sample and one outcrop sample both from within the staurolite zone contain synkinematic garnets and post-kinematic staurolite. The garnets are about 1-2 mm in diameter and are characterized by quartz-inclusion-rich cores and inclusion-free rims, indicating that there may have been two episodes of crystal growth. These garnets occur both within the matrix and as inclusions within the staurolite. The staurolite occurs as 1-2 cm porphyroblasts that cross cut the main fabric of the unit. Petrographic work shows that the foliation preserved within the staurolite (as quartz and garnet inclusions) is parallel to the foliation in the matrix. Overall, the petrographic features of the LFF are similar to that described for Early Proterozoic metasedimentary rocks located over 150 km to the northeast (Holm and Selverstone, 1990).

Detailed microprobe analyses were performed on both samples of the LFF. Garnet interiors exhibit uniform compositional patterns with an overall composition of almandine. Closer to the rims, the almandine and pyrope content increases and the grossular and spessartine content decreases, a trend that suggests prograde garnet growth. These compositional changes appear to correspond with the transition from inclusion-rich core to an inclusion-free rim. However, the textural change within the garnets is abrupt whereas the compositional change is gradational.

The LFF contains appropriate mineral assemblages on which geothermobarometry can be performed. We applied the garnet-biotite thermometer (Ferry and Spear, 1978; Hodges and Spear, 1982) and the garnet-plagioclase-biotite-muscovite barometer (Ghent and Stout 1981; Hodges and Crowley, 1985) to the LFF samples in order to determine the pressure and temperature conditions during garnet growth. Core analyses gave temperatures of 450-500°C and pressures of 5-6 kbar. Since only quartz occurs as inclusions within the garnets we used matrix plagioclase, biotite, and muscovite compositions in order to estimate the pressures of garnet core growth. Rim analyses yield higher temperatures of approximately 500-550°C and similar pressures of 5-6 kbar. The isobaric garnet growth we infer presumes that matrix plagioclase did not change in composition during garnet growth. These results concur with previous work done in other areas of the orogenic belt (Holm and Selverstone, 1990).

We interpret the inclusion-rich core of the garnets to represent syntectonic mineral growth during the Penokean orogeny. However the timing of late garnet rim and staurolite growth is uncertain. It is possible that both the garnet rims and the staurolite grew just after the formation of the foliation within the rock. In this scenario, the 'peak' metamorphic conditions would be associated with conductive relaxation after crustal thickening during the orogeny (Holm and others, 1988). Alternatively the garnet rim and late staurolite growth could have

occurred much later, perhaps as a thermal response to the ~1770-1760 Ma post-tectonic magmatism in the region. If so, then the 'peak' metamorphism would yield pressure and temperature conditions well after the Penokean orogeny. In this second scenario, the discordance between 'peak' metamorphic pressures (5-6 kb) and the emplacement pressures determined for the post-tectonic plutons (3.0-4.5 kbar, Darrah and Holm, 1995) would require rapid uplift concomitant with plutonism.

$^{40}\text{Ar}/^{39}\text{Ar}$ hornblende cooling dates may allow us to distinguish between the two scenarios presented above. Country rock hornblende dates older than ~1770 Ma would indicate temperatures below 500°C prior to pluton intrusion, thus ruling out the second scenario. Three hornblende separates from widely scattered samples of both Archean rocks and metamorphosed Early Proterozoic rocks to the east of the LFF all yield dates approximately coeval or slightly younger than the age of the plutons, and approximately concordant with the uniform 1750-1760 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ biotite dates of Holm and Lux (1996). Thus, although somewhat preliminary (more hornblende dates are currently being processed), the data at present may suggest a major period of rapid unroofing of this portion of the Penokean orogenic belt during a pulse of post-tectonic plutonism. The new results presented here are consistent with the occurrence of a proposed episode of orogenic collapse of the Penokean orogeny (Holm and Lux, 1996; Schneider and others, 1996).

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MICHIGAN MINERAL LEASE EXPLORATION DATA INVENTORY

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Upon termination of a metallic or nonmetallic mineral lease on State of Michigan owned minerals land, exploration data, geological records and samples, including drill cores and cuttings, from the work performed are submitted to the State to become part of the public record. Periodically, exploration information collected by companies during work on private land leases is also donated to the State.

Records are on file for exploration and mining activity for numerous mineral commodities. Past leases involved efforts to locate and/or mine copper, diamonds, gold, iron, limestone and dolomite, uranium and associated precious and base metals.

The exploration information is now inventoried on a computer database which allows access by county name, town and range, company name or State lease number, etc. The inquiry indicates if geological or geophysical work was performed, if any drilling was done, what type and any drill log confidential status. It also lists if any drill core, cuttings or other samples or assays were submitted and additional information.

Information listed in the inventory is kept in hard copy files which may be reviewed on an appointment basis. Geologic and geophysical data on file may prove to be an important lead to the future understanding of Michigan's geologic and mineral resources. Commodities located in the past may now be economic to produce. Also, the lack of known specific resources in an area may suggest that expenditure of new exploration dollars would be better used in another Michigan location. Additionally, terminated lease status may be determined for a parcel other companies are interested in leasing so their exploration activities can take place.

The quantity and quality of the information on file varies drastically from lease to lease. The type of lease, or contract, the years that the lease was in effect, the amount of work done on the property and the public consciousness of the lessee all play a part in determining what eventually is submitted to be placed into open-file status.

The leasing of State owned minerals is a function long managed by the Minerals Lease Management Section, Real Estate Division of the Michigan Department of Natural Resources (MDNR). For many years the collection of exploration data and samples at the termination of the leases was handled by the Michigan Geological Survey Division (GSD). However, during the split of functions of the MDNR, October 1, 1995, the GSD was placed into the new Michigan Department of Environmental Quality (DEQ). During this process the limited general geologic, metallic and nonmetallic mineral resources and groundwater resource related functions, and staff, of the GSD were transferred to the Real Estate Division (RED) of the DNR. RED geologic staff and functions are located in Lansing, Escanaba, and Marquette.

Through the above changes, the geologic records from terminated State mineral leases now reside in files of the RED/MDNR. Any geological drill core or other samples submitted at lease termination are then placed in the GSD/DEQ's Geological Core and Sample Repository for public use. Both the Mineral Lease Data Inventory and the Repository are located in the Marquette, MI locations of the DNR and the DEQ.

For information about the Mineral Lease Data Inventory, call Milt Gere, RED/DNR, or for information about the Repository, call Bill Swenor, GSD/DEQ. Both can be reached via phone at 906/228-6561,

GEOCHEMICAL SOURCE CHARACTERISTICS AND DIAGENETIC TRENDS OF THE VIRGINIA FORMATION, MESABI IRON RANGE, MINNESOTA

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Understanding the evolution of the Animikie Basin is integral to understanding the regional tectonic framework in the Great Lakes area during the Early Proterozoic. The Animikie Basin contains a number of approximately correlated shale to turbidite sequences that form the youngest unit within the Animikie Group. In the Mesabi Iron Range of northern Minnesota, the Virginia Formation is composed dominantly of shales and is relatively undeformed. The geochemistry of sedimentary rocks provides powerful information concerning basin evolution. However, there are a number of complexly interactive parameters that control the composition of sedimentary rocks. The ideal characteristics of elements that could be used to quantify the original composition of the ultimate igneous source are relative immobility in most natural fluids and different enough behavior during igneous differentiation as to be sensitive to source composition. Although no element is completely immune from chemical attack, it is well known that the rare earth elements and Th and Sc are well suited for characterizing source compositions and Nd isotopes provide valuable constraints on the antiquity of the sources. Compared to post-Archean Australian average shale (PAAS), shales of the Early Proterozoic Virginia Formation have light rare earth element enriched patterns and high abundances of rare earth elements, low Th/Sc ratios that are correlated to Th abundances and high La/Th ratios. The Sm-Nd isotope composition of Virginia samples indicates a source that was recently derived from a long-term light rare earth element depleted reservoir, and the trace element character indicates it was a continental source. These geochemical data best fit a young differentiated arc as the dominant source for the Virginia Formation.

Elements are variably susceptible to chemical attack by surface waters and thus well understood trends in chemical composition are created during weathering. Published reports have showed that major element variations predicted by thermodynamic calculations are generally consistent with trends in weathering profiles. In contrast, many diagenetic reactions may create an approximately reverse trend from weathering. Accordingly, estimates of weathering intensity based on chemical compositions of sedimentary rocks will tend to be minimum estimates. Major elements and alkali and alkaline earth trace elements in the Virginia Formation are strongly correlated and are substantially divergent from igneous differentiation trends. Ca contents are extremely low, mostly less than 1 wt. %. Thus the sediments' compositions are almost totally controlled by aqueous alteration during sedimentary processes. Two main lines of evidence suggest the measured compositional trends are largely products of diagenetic/metamorphic reactions. First of all, a SHRIMP U-Pb zircon age from an ash layer near the base of the Virginia Formation constrains the time of deposition to be about 1.85 Ga. However, a Rb-Sr isochron from the Virginia Formation is very well correlated and yields a 1.6 Ga age estimate (Peterman, 1966, GSA Bulletin), consistent with a time of pervasive resetting of the Rb-Sr system in the region. Secondly, on a Al_2O_3 - Na_2O + CaO - K_2O ternary (CIA, chemical index of alteration) the samples lie along a mixing line between illite and albite, ranging from about 50 to 80 mole % albite. Illite and albite are commonly formed during burial diagenesis. The strong correlation between $\text{K}_2\text{O} / \text{Na}_2\text{O}$ and Rb/Sr is likely a product of various mixtures of these diagenetic/metamorphic minerals, and thus the 1.6 Ga Rb-Sr age approximately dates the time of their formation.

WAS LITHOSPHERIC DELAMINATION AN IMPORTANT PROCESS IN THE EVOLUTION OF EARLY PROTEROZOIC COLLISIONAL OROGENS?

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Mantle lithospheric delamination has been proposed as a ubiquitous process in Phanerozoic collision zones to the point that it may require a paradigm shift in our understanding of how collisional orogens evolve. The process of rapid mechanical thinning of the mantle lithosphere beneath an orogenic belt ("delamination") has fundamental implications for both the chemical and structural evolution of continents (Nelson, 1991, 1992). Although geophysical data from relatively young orogens seem to support the delamination hypothesis, these data (i.e., deep seismic profiling) seem limited (at best) for assessing delamination in very ancient orogens. Evaluation of its importance in Precambrian orogenic belts must rely, unfortunately, on less direct evidence. Two consequences of mantle lithospheric delamination are rapid isostatic uplift of the overlying overthickened crust (orogenic collapse) and heating of the lower crust resulting in generation of post-tectonic magmas (Turner and others, 1992). Investigations of the post-collisional uplift history and its relation to post-tectonic plutonism may therefore be a means to assessing the delamination hypothesis in the Precambrian. We summarize below evidence from two Early Proterozoic orogens in the North American midcontinent which may be at least consistent with (though not exclusively indicative of) the delamination hypothesis.

Southern Trans-Hudson orogen. In the southern Black Hills of South Dakota, medium pressure rocks metamorphosed during an Early Proterozoic collisional orogeny where uplifted at least 8-10 km before being intruded by the post-tectonic Harney Peak Granite at ~1700 Ma. Abundant thermobarometric data indicate that the granite was emplaced at midcrustal depths (12-14 km) and thermochronologic data suggest emplacement was followed by a ~200 Ma period of stability and tectonic quiescence with little uplift. Isotopic and trace-element data from the granite (Nabelek and others, 1992a, b) indicate that at least the interior portions of the pluton were derived from high-extent vapor-absent melting of biotite in deep-seated Archean/Early Proterozoic metasedimentary rocks. The generation of the granite has commonly been attributed to thermal relaxation of the overthickened crust following collision. However, heat-flow modeling results suggest that thermal relaxation was probably not a viable mechanism for achieving the >850°C temperatures (Vielzeuf and Holloway, 1988) necessary to produce voluminous crustal melts in the Black Hills. We speculate that generation of the Harney Peak Granite magma and the crustal uplift which preceded it may have been the result of thinning of the mantle lithosphere (delamination) beneath the southern Black Hills. This scenario seems supported by the fact that, in the whole of the Black Hills, the Harney Peak Granite is spatially associated with the deepest exposed Early Proterozoic country rock. Because uplift preceded midcrustal granite emplacement, we emphasize that this spatial association is not related to *in situ* melting of the deepest-exposed portions of the orogen. Rather, preferential intrusion into the deepest exposed rocks is exactly what would be expected if both uplift and melt generation were the result of the delamination process. Recent age constraints suggest syncollisional regional metamorphism at ~1740-1750 Ma suggesting a time-lag of 30-50 Ma between collision and the proposed delamination.

Penokean orogen. In the Lake Superior region Early Proterozoic post-Penokean granites intruded into rapidly uplifting crust beginning around 1770 Ma. Holm and Lux (1996) suggested that the granites represent deep crustal melts related to an episode of orogenic collapse perhaps triggered by mantle lithospheric delamination. Abundant post-Penokean NE-striking basaltic dikes (in both central Minnesota and Wisconsin) which were likely intruded synchronously with

or just after the granites are evidence for a significant mantle thermal input into the base of the crust (Van Wyck, 1995). The spatial and temporal relation of rapid uplift, melting of the lower crust and basaltic dike intrusion is consistent with an episode of mantle lithospheric thinning. Alternatively, recent evidence for a somewhat younger (~1730 Ma) deformational and metamorphic event suggests the post-Penokean reheating event responsible for magma generation might be related to distant subduction to the south (Van Wyck, 1995).

Concluding remarks. The summaries presented above suggest that for the southern Black Hills crustal thinning preceded granite emplacement whereas for the Penokean orogeny igneous intrusion occurred during tectonic thinning. We suggest that this difference in the relation between plutonism and uplift between the two orogenic belts may be more apparent than real by simply being an artifact of the level of exposure available for us to investigate. That is, the Penokean orogenic belt exposes midcrustal depths *during* the proposed collapse episode whereas the Black Hills exposes midcrustal depths *after* the period of post-collisional uplift.

Nelson (1991) has suggested that the delamination process may actually involve both the mantle portion of the lithosphere and portions of the lower crust, making it perhaps a critical step in both the chemical and structural evolution of continental lithosphere. Nelson's proposed view of craton evolution relies heavily on uniformitarian principles by invoking processes observed in active or young orogenic belts to have occurred throughout the Earth's history. Detailed studies of the exposed mid- and lower crustal roots of Precambrian orogenic belts will provide one important test of Nelson's unified view of craton evolution.

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GENESIS OF A TIMISKAMING-LIKE SEQUENCE IN THE SOUTHERN WAWA SUBPROVINCE, NORTHEASTERN MINNESOTA

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An unusual conglomeratic sequence sandwiched between two units of Archean graywacke in the Virginia Horn (Fig. 1) has been recognized since the 1960s as having attributes of the classic Timiskaming in the Kirkland Lake area, Ontario. Since that time, considerable attention has been given to such sequences throughout the Superior Province, and many are now well documented. The focus on the Timiskaming was fueled in part by the association of these sequences with major gold camps. Most Timiskaming-like strata were deposited in structurally controlled basins inferred to be the product of localized extension during early regional transpression of the greenstone sequences (i.e., pull-apart basins) prior to metamorphism which accompanied D2 deformation. Because they are the youngest of Archean supracrustal rocks, the Timiskaming-like sequences are unique temporal pins in the structural and stratigraphic evolution of the Superior Province.

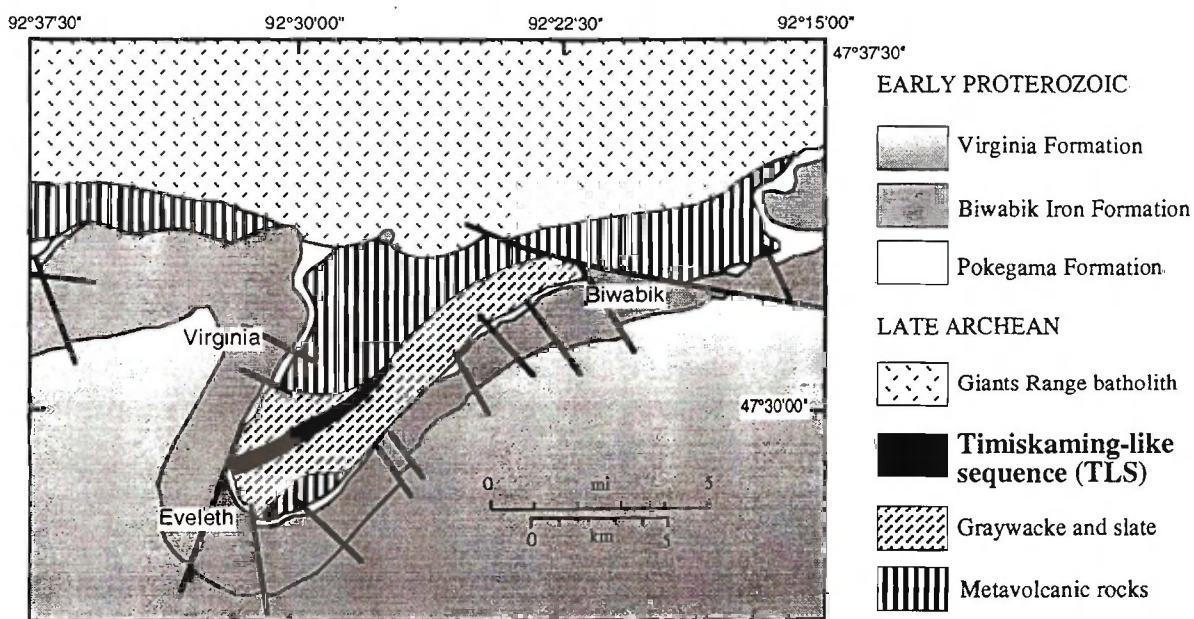


Figure 1-- Simplified geologic map of the Virginia Horn area. The term "Virginia Horn" refers to the hook or horn-shaped distribution of Early Proterozoic Biwabik Iron Formation in the vicinity of Virginia, Minnesota, and is applied to the area surrounding it. The iron-formation onlaps Archean bedrock, which is likely the southernmost exposures of the Wawa subprovince.

The Timiskaming-like sequence (TLS) in the Virginia Horn lies within an east-trending, broadly synclinal succession of graywacke and slate underlain by mafic to intermediate volcanic rocks. It forms a northeast-trending structural wedge at least 5 km long and a maximum of 1 km thick. The TLS is homoclinal, steeply dipping, and consistently south facing. Early Proterozoic strata conceal the western part of the TLS, and the sequence is terminated on the east by a fault. Although the boundaries of the TLS are rarely exposed, a composite section can be inferred in a few areas from a combination of drill core and outcrops. The sequence is divided into several units that vary in thickness and character along strike. The basal unit is sandstone and pebbly conglomerate, which varies from absent to 30 m thick, and coarsens up-section. It is composed of detritus derived from older greenstone, and distinctive quartz phenocrysts eroded from the quartz-feldspar porphyry that intruded the greenstone. The basal contact is a fault in most places; but locally is unconformable atop a variety of older rocks. A thin and discontinuous volcanic unit containing

flows and hypabyssal sills of a distinctive, calc-alkalic, hornblende trachyandesite porphyry (HAP) is present locally above the basal unit. Where the volcanic unit is absent, laterally equivalent strata are dominated by HAP clasts. Where the volcanic unit can be seen in outcrop, it grades into flowtop breccia, agglomerate, and conglomerate made up almost entirely of clasts of HAP. This conglomeratic unit makes up the bulk of the TLS sequence and is composed of poorly sorted, clast-supported, and vaguely graded beds. Clasts within the conglomerate become more diverse in texture and composition up-section, and bedding, grading, and sorting are better developed.

This stratigraphic sequence records a progression from gentle subsidence of a sediment-starved basin, followed by volcanism, basin collapse, and in-filling with coarse detritus. Clasts in the conglomeratic unit were initially derived largely from intrabasinal volcanic rocks, but progressively more extrabasinal material was supplied as the basin's watershed expanded. The absence of demonstrably lacustrine or fan-delta deposits implies that much of the deposition was subaerial. The great thickness of coarse, poorly sorted conglomerate indicates deposition within alluvial fans, and local bedded and cross-bedded sandier units probably have a fluvial origin. Lateral continuity of individual units is difficult to establish, in part because of abrupt facies changes along strike, which are inferred to be the result of deposition in the many sub-basins common in pull-apart settings.

Earlier workers in the Archean of the Virginia Horn attempted to link deposition of the TLS with that of the enclosing graywacke-slate sequence by inferring that the TLS represented proximal turbidite channel deposits, while the graywacke and slate units were deposited as distal turbiditic fans. Remapping, which utilized outcrop and a series of cores drilled by exploration companies along the basal contact of the sequence (which were not available earlier), demonstrates that they do not represent a depositional continuum for the following reasons:

1. Structural data indicate that the graywacke-slate sequence is twice folded, and in fact much of the graywacke strata was overturned during D₁, prior to deposition of the TLS. Locally recumbent, east-trending F₁ folds are cut at an acute angle by the basal unconformity and faults which bound the Timiskaming-like sequence.
2. Quartz-feldspar porphyry intruded the greenstones, but not the TLS, and in fact provided detritus to the TLS.
3. Flows, intrusions, and clasts of HAP are unique to the TLS, and detrital hornblende derived from HAP is common in conglomerate matrices and associated sandstone units. Detrital hornblende does not occur in the graywacke-slate sequence.
4. Hornblende-phyric dikes, texturally similar to and inferred to be feeders of HAP flows, cut all rock types.
5. A sharp contrast in depositional style occurs between the resedimented facies graywacke-slate sequence, and the volcanic and alluvial fan-fluvial facies deposits of the TLS.

The TLS contains all the characteristics of pull-apart basin deposition, including structural and unconformable boundaries, abrupt lateral facies changes, thick and variable alluvial sediments, and the association of unique volcanism. Although other conglomeratic units in Minnesota may be candidates for a similar designation (Seine Group in the Rainy Lake area and Okishkemucie conglomerate in the Knife Lake Group), none has the unique combination of Timiskaming attributes present in this sequence.

Support for mapping in the Virginia Horn is being provided by the State Legislature and is administered by the Minerals Coordinating Committee.

Identifying Geologic and Other Potential Resources From Michigan's Abandoned Underground Mine Inventory

Allan M. Johnson(1) and Milton A. Gere, Jr.(2)

Introduction. A two-year contract to inventory, document and map abandoned underground mines in the State of Michigan was awarded to Michigan Technological University (MTU) by the Geological Survey Division (GSD) of the Michigan Department of Natural Resources (MDNR) in late summer of 1995. The project is now being overseen by the Real Estate Division (RED) following recent changes in the structure of the MDNR.

The inventory is needed to permanently preserve a data base on the location and condition of underground mine openings and to identify and rank any unsafe conditions found during the field investigation phase of the project. These data will help planners to avoid undermined areas for future development and will call attention to the conditions needing corrective action to protect public safety.

Similar work on abandoned iron ore mines in Iron County was done in the 1970's for the GSD-MDNR in which problems of mine subsidence and acid drainage were addressed (Johnson and Frantti, 1978). An inventory of mines was also done (MacDonald and Johnson, 1984). This research has been useful for planning purposes and in preserving a record of the mines which otherwise might have been lost with the passage of time, and also in documenting first-hand knowledge from aging miners, as underground mining activity of the last 150 years becomes a relic of the past.

Goals. The project requires a computerized mine map data base compatible with MIRIS (Michigan Resource Information System), the State's Geographical Information System. This will preserve mine map data and will ultimately make it available electronically to the public. The three major requirements of the project are:

1. To provide accurate information on the location and extent of underground openings for each of the more than 500 abandoned and closed underground mines in Michigan. Selected mine map information will be digitized and stored in a computerized data base using AutoCAD software.
2. To provide information and maps for each of the underground mines on a county-by-county basis. This will include mine name, location, years of operation, production records, mine ownership, mine operator, number of shafts and other openings to the surface, subsidence pits if present, and other relevant data obtainable from records and mine maps. Also included will be assessments of the condition of shafts and other surface features at each mine based upon field observations.
3. To identify and rank potential problems at abandoned mines in terms of public safety from open shafts, caving around shafts, deterioration of shaft seals or caps, subsided areas, and other unsafe

conditions. Assistance of mining company personnel, county mine inspectors and other knowledgeable individuals will be important in the field inspection phase of this project.

Opportunities and Attributes. It is recognized that abandoned mines do possess esoteric attributes. For example, many old mines have historical significance which, if enhanced by remnants of old mine buildings and artifacts, may be of value for tourism. A good example is the Keweenaw National Historic Park.

On-going research has identified a number of Michigan underground mines as sites of active bat hibernation during winter months (Millie Hill Mine in Iron Mountain). The International Bat Conservancy, seeking to preserve these mines, reports that large numbers of bats migrate from surrounding states and Canadian provinces to hibernate there.

Flooded mines represent a potential resource of huge volumes of water suitable for industry (Norrie Mine, Ironwood) and, in some cases, high quality potable water (Champion Mine, Painesdale). Flooded mine pools are also a source of readily available geothermal energy suitable for extraction using heat pump technology (Osceola Mine, Calumet).

Formerly discarded mine wastes, waste rock and mill tailings, are becoming recognized as valuable raw materials for industry. Examples include using these wastes as aggregate (iron and copper districts) ice and snow traction (Keweenaw Peninsula) and potentially as raw materials in manufacturing such products as floor and ceiling tiles, thermal insulation, building and construction materials and a variety of speciality products. Tailings from the Republic Mine are being used for portland cement manufacture at Lafarge Corporation in Alpena.

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AN ANCIENT LANDSLIDE AT "RED ROCKS", KEWEENAW BAY, MICHIGAN

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At the south end of Keweenaw Bay is an outlier of Jacobsville Sandstone, red along the highway and purplish grey along the lake shore where the bottom 1-3 m of the section is exposed, and rests on Michigamme slate (Fig.1). There the sub-horizontal Michigamme surface exhibits parallel striations, leading Murry (1955) to propose a pre-Jacobsville period of glaciation. Conversely, on the basis of bedding slips in the sandstone, and evidence for a non-glacial paleoclimate, I suggested that the striations were produced by basal pebbles as the entire sandstone mass slid northerly (Kalliokoski, 1982).

Additional detailed mapping last summer revealed a clayey fault, traceable for about 15 m along the slate/sandstone contact (Fig.1). At Sta.43 a strand of this shear rises obliquely (dip 15° SW) through a 40 cm sandstone bed, and merges into the base of the overlying conglomerate. The orientation of the fault indicates that the upper block moved northeast. About 20 m southwest of this fault is a larger one along which sedimentary beds have moved up along a low-angle ramp fault (strike N35 W, dip 30° SW: Fig.1, Sta.23; Fig.2). The orientation of this fault also denotes northeast movement. Moreover, features in Fig.2 indicate that the footwall conglomerate first moved along a bedding fault, and at this locality, up an inclined fault (a stage beyond that illustrated at Sta.43). When movement of this conglomerate had slowed or ceased, the proximal part of the conglomerate bed over-rode the previously ramped one.

Below the fault (Fig.2; Sta.43) there are parallel striations on the Michigamme slate surface: 12 at 54°-234°, and 2 faint ones at 90°-270°. The prevalent direction is the same as for the fault movement vectors, and suggests strongly that the striations and faults formed within the same dynamic system.

The elevation of Michigamme slate outcrops south of the Bishop Baraga statue and along the lake shore suggest that the sub-Jacobsville surface slopes about 6° northerly.

The above evidence indicates that the sandstone outlier slid northeast along bedding faults, one along the smooth Michigamme slate surface and others along higher bedding surfaces. Where a more distal portion of the mass stopped moving, stresses within the system caused the more proximal portions of beds to override the distal ones, as is characteristic in landslides and along zones of imbricate thrusting.

Mass movement of the sandstone probably occurred in post-Glacial time. This may be the cause for the sub-vertical, north dipping fractures in the highway exposure, not seen anywhere else in Jacobsville Sandstone outcrops, and for the more irregular jointing in the lowermost beds. The purplish color in the basal sandstone may be a product of groundwater flow above the impermeable Michigamme basement.

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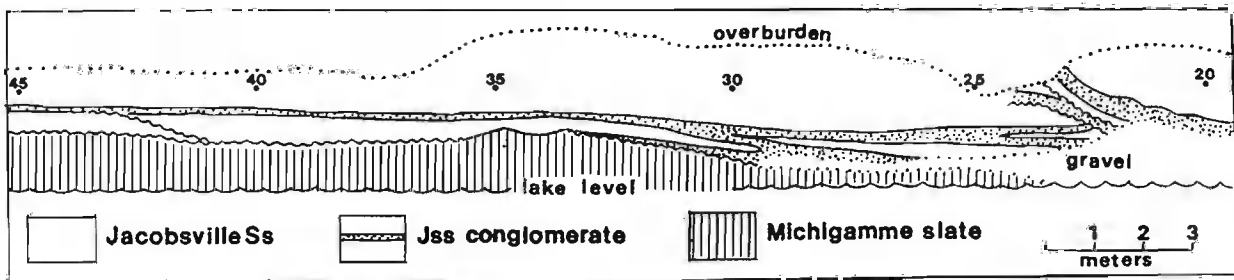


Figure 1. Vertical shore outcrop; azimuth of profile 55° . Jacobsville Sandstone is in fault contact (Wavy line) with Michigamme slate, and rests on striated slate at Sta. 43. At Sta. 43 and 23 are inclined thrust faults, indicating that higher strata have moved NE.

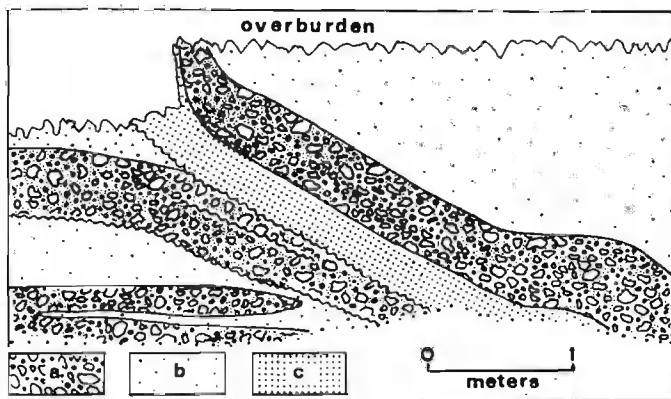


Figure 2. Detail at Sta. 23; a, congl., b, sandst., c, indurated sandst. Lower inclined congl. slid on its base and up an inclined fault surface. Later the sandst. and congl. of the upper plate were thrust into place.

Aeromagnetic Map of Lake Superior

by
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Introduction

An aeromagnetic map of the Lake Superior region (figure 1) was compiled as part of the Great Lakes International Multidisciplinary Program on Crustal Evolution (GLIMPCE). The magnetic anomaly data set was compiled from digitized and digital data acquired from a diverse group of magnetic surveys. This abstract describes the procedures used to reduce and merge the individual aeromagnetic surveys to make the Lake Superior aeromagnetic map.

Aeromagnetic Surveys

The aeromagnetic surveys were flown with flight-line spacings ranging from 0.25 mi (0.4 km) to 3 mi (4.8 km). The surveys were flown in draped mode (constant elevation above terrain or water) at elevations ranging from 300 ft (91.44 m) to 1000 ft (304.8 m). Figure 2 shows the location of the surveys compiled to make the Lake Superior aeromagnetic map.

Data Reduction

Data set J, for the UP (Upper Peninsula Michigan), was only available as hand-contoured magnetic maps. Digital data were created by digitizing 1:24,000 and 1:62,500 magnetic maps. For maps with 0.5 mi (0.8 km) flight line spacings, data were generated by digitizing the intersections of contour lines with flight lines. In the case where individual surveys were flown at 0.25 mi (0.4 km), every other line was digitized due to the time allotted for the project and the expected anomaly resolution of the final product. Part of survey J was flown with flight line spacings of 1.0 and 3.0 mile (1.6 and 4.8 km). For greater control, these more widely spaced data were digitized both at contour intersections along the flight lines and at inflection points of contours between flight lines.

Gridding

For magnetic surveys E, F, G, H, and the seven sets that make up J, the total-intensity data were projected to the Lambert conic conformal projection (standard parallels of 42.5°N and 48.5°N and central meridian of 88.5°W) then gridded at an interval of 0.4 km using a computer program (Webring, 1981) based on minimum curvature (Briggs, 1974). Surveys A, B, C, D, and I were acquired in grid form and were reprojected and regridded to the above projection and grid interval specifications. The digital surveys (A, B, C, H) flown at a 0.25 mile (0.4 km) spacing were gridded at a finer interval of 0.2 km (0.125 mile) to honor the data more closely and then regridded to 0.4 km (0.25 mile) for the final merge. Surveys A and B were used to minimize edge effects along 83°W longitude, and therefore were not used in their entirety.

Reference Field Removal

The geomagnetic reference fields calculated for the date and location of the individual surveys were subtracted from the total-intensity grids to produce the residual total-intensity grids. The particular geomagnetic reference field removed depended on the year in which a given survey was flown and consisted of the definitive International Geomagnetic Reference Field (Sweeney, 1990) or in the case of the Minnesota Survey C, the American World Chart (AWC) Regional reference field (Peddie, 1976).

Merging

Before merging data sets, magnetic field values of each survey grid were adjusted by a constant amount using survey D as an absolute datum, to minimize discontinuities at merge boundaries. The original observation surfaces of the data have been maintained which may also account for slight discrepancies at merge boundaries.

Data set J was created from seven separate grids by removing two grid cells from the edges of each and assigning values across the gap using the one-dimensional splining techniques described by Bhattacharyya and others (1979). The major surveys denoted on the index map were then merged by removing one and two grid cells respectively, from the borders of survey E and the remaining sets. The resultant grids were combined leaving data gaps within the final composite grid. These gaps were then assigned data values using the computer program MEGAPLUG (Phillips and others, 1993), by the same minimum curvature technique used by Briggs (1974) and Webring (1981) when gridding. Data were then removed from areas where no reasonably compatible surveys exists (white areas in the southwest part of figure 1). Some margin areas along latitude 46°N contain data created by the process, but due to their minimal impact, they have been retained.

The final compiled data set has a grid spacing of 0.4 km (0.25 mi) and is projected using a Lambert conformal conic projection (standard parallels of 42.5°N and 48.5°N, central meridian of 88.5°W, and base latitude of 46°). The gridded magnetic data are available from the U.S. Department of Interior, EROS Data Center (Kucks, 1990), or from NOAA (Hittelman and others, 1992). The color aeromagnetic map (figure 1) was produced from the above grid using the program GDRELIEF (unpublished USGS program, information available from the author).

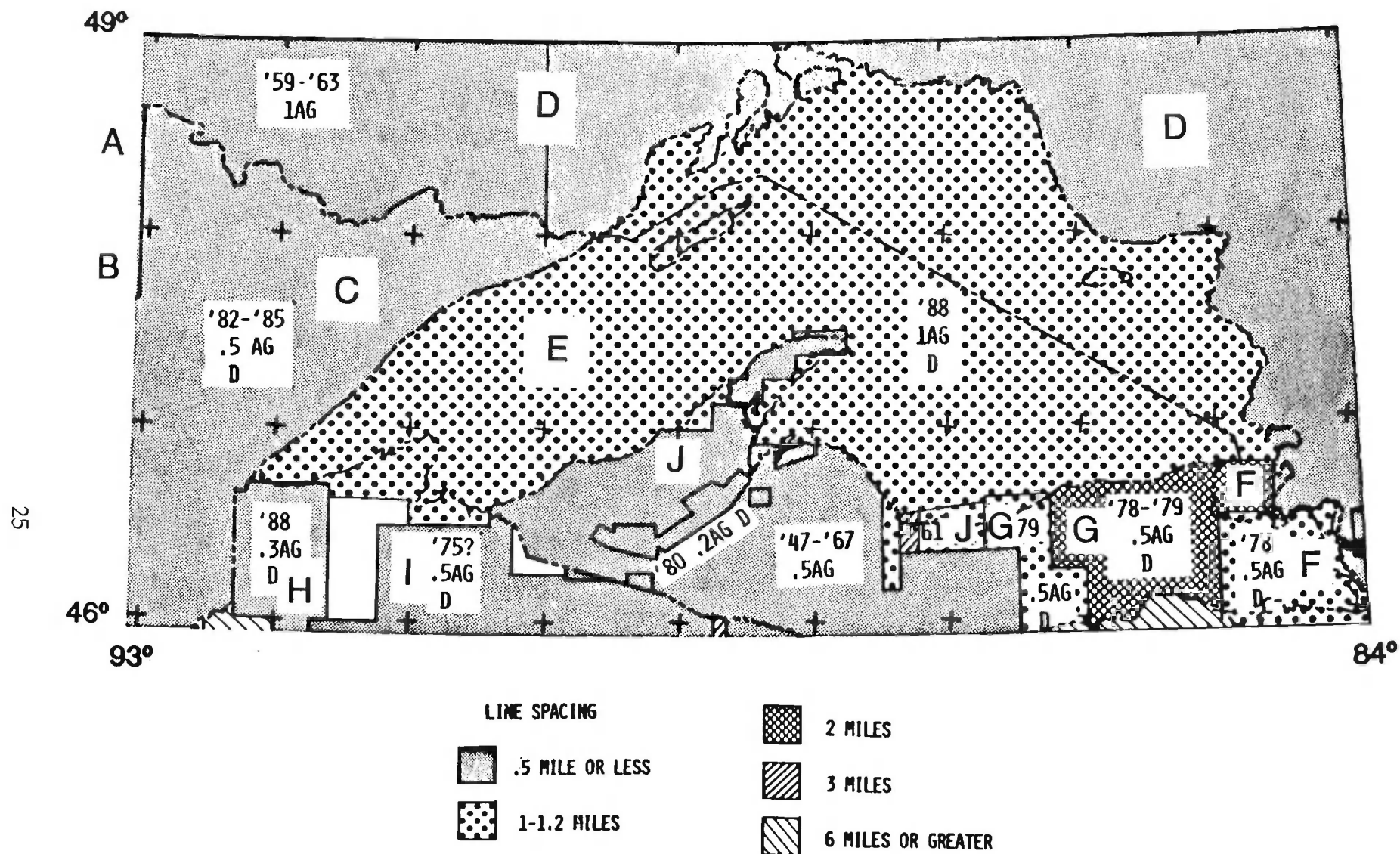
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Lake Superior Aeromagnetic Survey Index

Figure 2. Index map showing the location of individual surveys, flight line spacing, year(s) flown, flight altitude in thousands of feet above ground (.5AG = 500 feet above ground), and data format (D = digital).

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Glimpce/Lake Superior Magnetics

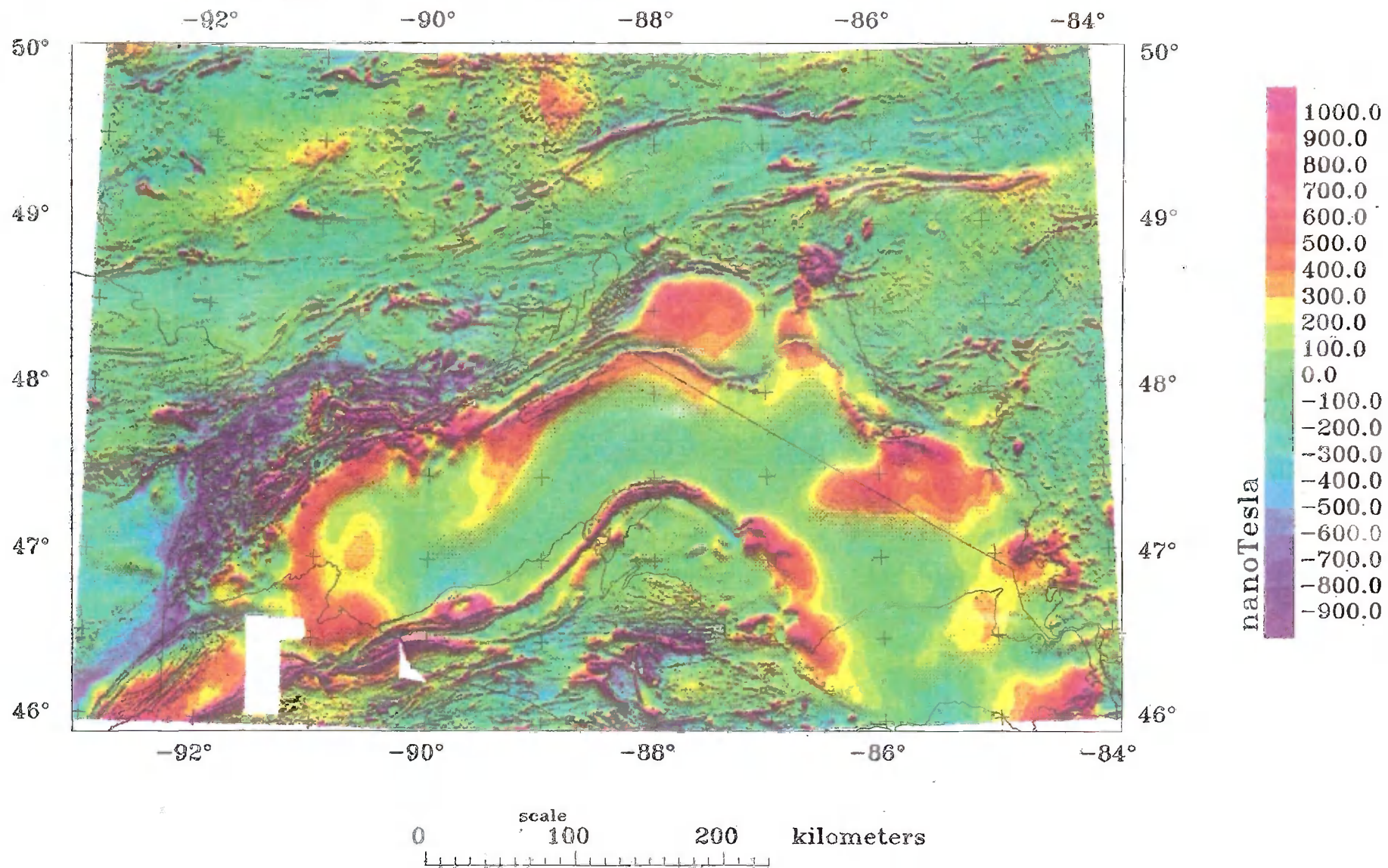


Figure 1. Kucks and Horton

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LATE HOLOCENE LAKE SUPERIOR -- ISOSTATIC AND CLIMATIC LAKE-LEVEL CHANGE. LARSEN, Curtis E., U. S. Geological Survey, Reston, VA 22092

Beach-ridge complexes along the south shore of Lake Superior record a composite history of lake-level change from 5,000 B.P. to the present that includes the effects of past climatic episodes superimposed on differential isostatic uplift of the basin. The pattern of isostatic uplift plays a dominant role in reconstructing past lake-level changes from coastal landforms.

For Lake Superior, uplift increases with distance northeastward from Duluth, Minnesota, to Michipicoten, Ontario. Isobases of equal movement trend from northwest to southeast across the basin. The outlet to the basin at Sault Ste. Marie is rising at an apparent constant rate of 0.27 meter per century relative to Duluth. Michipicoten, Ontario, is rising at about 0.5 meter per century relative to Duluth. The flow rate through the outlet channel, however, controls the mean level of the lake. For modern Lake Superior, the outlet is rising more rapidly than the U. S. shore of the lake. Such differential movement raises the mean level at Duluth and submerges that area at a rate of 0.27 meter per century. Along the Canadian shore, uplift exceeds that at the outlet so that the mean level falls relative to the outlet. This pattern of submergence of the southern shore and emergence of the northern shore is a relatively recent event linked to the uplift of the St. Mary's Rivers rapids above the surface of Lake Huron at about 2,100 B.P.

Between 5,000 and 2,100 years ago, Lake Superior was part of the Nipissing and Algoma phases of the upper Great Lakes. A confluent lake linked the three basins at Sault Ste. Marie. The mean level of the lake was controlled mainly by the outlet to Lake Huron at Port Huron, Michigan. Coastal landforms from the Nipissing and Algoma phases are common to all three lake basins. These landforms have been uplifted relative to the controlling outlet at Port Huron and correlate directly between Lake Huron and Lake Superior near Sault Ste. Marie. Following the separation of Lake Superior from the lower lakes at 2,100 B.P., a different record of lake-level change developed. Beach-ridge complexes near Sault Ste. Marie and along the Canadian shore of Lake Superior and Lake Huron have been raised above the control of their controlling outlets; these complexes preserve a subaerial lake-level record from 5,000 B.P. to present. After 2,100 B.P. Lake Superior has its own unique lake-level record. Uplift of the St. Mary's River relative to Duluth has caused a progressive submergence of the coast as the outlet has risen.

Near Duluth and the Apostle Islands, much of the coastal geomorphological record is submerged. At least 5.8 m of submergence has occurred at Duluth and about 4.4 m at the Apostle Islands since uplift of the St. Mary's rapids became the sole control of Lake Superior 2,100 B.P. The Nipissing level of the confluent Great Lakes that is indicated by a raised coastal beach and dune complex at an elevation about 13 m above the surface of Lake Superior near Sault Ste. Marie is preserved as an apparent inner barrier island system preserved in marshes at Bark Bay and Big Bay State Park, Wisconsin, and most noticeably as an inner bar system bordering Duluth harbor at Superior, Wisconsin. Prominent beaches at the lakeward edges of these bays and the outer barrier island at Duluth represent the probable position of the Algoma beach (ca. 3,500 B.P.). This landform has continued to build vertically as the mean level of Lake Superior has risen. The record is complex, but detailed studies of beach-ridge complexes and marshes (such as Bark Bay) indicate steadily rising water levels in this part of Lake Superior controlled by uplift of the outlet at Sault Ste. Marie. Recent submergence is also evidenced by drowned *in situ* trees near Ashland, Wisconsin, and in Duluth harbor. Our studies suggest that the rate of uplift at Sault Ste. Marie has remained constant for at least the past 4,000 years. The long-term prognosis for western Lake Superior is a continued rise in mean lake level, upon which may be superimposed both higher and lower lake level episodes related to climate changes.

The range of past climate-related fluctuations in Lake Superior is also significant. From an historical perspective, the range of Lake Superior levels from 1860 to present is 1.2 m or ca. ± 0.6 m about the mean. The earliest historical accounts from the 1830's and 40's suggest a range of 2.4 m (± 1.2 m) prior to construction of the Soo locks. Our most recent research results from submerged spit deposits at Bay Mills, Michigan, and the active Long Island spit at Ashland, Wisconsin, indicate that lake levels were 1.5 m lower than present about AD 1400 during the 'Medieval Warm Phase' and about 1 - 1.2 m higher during the early 1700's. The range of premodern lake level appears to have been on order of double the range of modern levels.

AGE AND GEOLOGICAL SIGNIFICANCE OF THE BARABOO QUARTZITE

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Post-Penokean mature red quartzites in the southern Lake Superior region (Baraboo, Barron, and Sioux Quartzites) provide important evidence on Proterozoic cratonic evolution. The Baraboo Quartzite has been re-examined to resolve the question of its age, identify its mineralogy, determine conditions of weathering in the source rocks and subsequent metamorphism, and evaluate the mid-Proterozoic tectonic regime in which the mature red quartzites were formed.

Age of the Baraboo Quartzite: the Baraboo Quartzite is unconformable on rhyolite (Dalziel & Dott, 1970; Dott, 1983), but was previously thought to be intruded by the Baxter Hollow granite (Gates, 1942). Both rhyolite and granite were interpreted to be correlative with 1760 Ma rhyolite and granite elsewhere in Wisconsin, and this interpretation has been confirmed by U-Pb zircon ages of 1754 ± 44 Ma for rhyolite from the north limb of the Baraboo syncline and 1752 ± 15 Ma for the Baxter Hollow granite (Van Wyck, 1995). Thus, a geological paradox arises: how could a mature quartz arenite, which is virtually devoid of feldspar, be closely associated in space and time with granite-rhyolite magmatism?

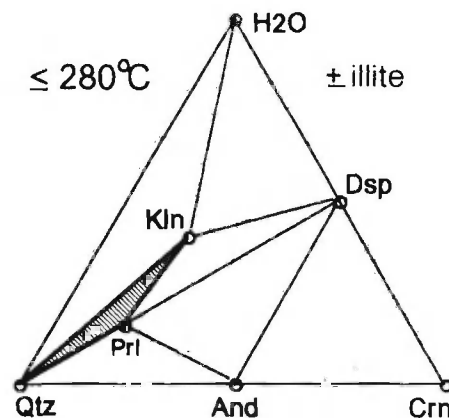
The quartzite-granite contact has been re-examined in Baxter Hollow, and in cores from eight drill holes that penetrated the quartzite-granite contact, which were obtained by the U.S. Army Corps of Engineers in 1959. There is no evidence in the field, or in any of the drill cores, that quartzite was intruded by granite. Shearing has developed near the contact, especially in granite, which has been transformed locally to illite-quartz semi-schist.

Among the drill holes that penetrated the quartzite-granite contact, material from the contact interval was recovered only in Hole No. 613, where there is a two-foot thick, reddish-purple zone of fine-grained hematite, quartz, illite, and kaolinite, which appears to be a regolith, between overlying pebbly quartzite and underlying, altered granite. Pebbles in the quartzite consist mostly of quartz, although a few pebbles of red, altered rhyolite occur. We conclude that the Baraboo Quartzite is unconformable on the Baxter Hollow granite, and that shearing was localized along the contact between these two competent rock types during later folding.

The two-foot interval between quartzite and granite may represent a paleosol, which was derived from weathering of the underlying granite and modified by subsequent shearing and metamorphism, and a chemical investigation is in progress to test this hypothesis. In addition, detrital zircons, some of which are euhedral, have been separated from the quartzite and are being analyzed to test whether any were derived from 1760 granite-rhyolite sources.

Mineralogy: sheet silicates in the Baraboo Quartzite are dominated by pyrophyllite, $\text{Al}_4\text{Si}_8\text{O}_{20}(\text{OH})_4$, and kaolinite, $\text{Al}_4\text{Si}_4\text{O}_{10}(\text{OH})_8$, which occur interstitially in quartzite and in pyrophyllite-rich layers. K-mica is illite, $\sim \text{K}_{1.5}\text{Al}_4[\text{Si}_{6.5}\text{Al}_{1.5}\text{O}_{20}](\text{OH})_4$, and occurs interstitially in quartzite, in the regolith(?) in Hole 613, and as the alteration product of feldspar in granite. Diaspore, $\alpha\text{-AlO}(\text{OH})$, was discovered in quartzite in Holes 613 and 614A, where it is associated with pyrophyllite, kaolinite, and illite. The presence of such aluminous minerals in the Baraboo Quartzite indicates derivation from maturely weathered soil, such as laterite, and signifies a mid-Proterozoic episode of intense chemical weathering and leaching of alkalis.

Metamorphism: the common assemblage, quartz+pyrophyllite+kaolinite+illite, limits the temperature of metamorphism to less than 280°C at an assumed P(H₂O) of 500 bars. However, kaolinite occurs as micron-scale interlayers in pyrophyllite, and if kaolinite is a retrograde mineral, rather than prograde, temperatures could have been as high as 350°C, which is the stability limit of pyrophyllite. Diaspore in the Baraboo Quartzite is always separated from quartz by pyrophyllite, and may represent relict detrital grains, which were derived from a lateritic source, and which were protected by surrounding pyrophyllite from complete reaction with quartz during metamorphism.



Geological Significance of the Baraboo Interval: the Baraboo interval was defined by Dott (1983) as a sequence of sedimentation, deformation, and metamorphism in the time span of 1450 to 1750 Ma in the southern Lake Superior region. Deposition of the Baraboo, Barron, and Sioux quartzites was thought to have occurred after 1750 Ma, but prior to 1650 Ma, which was a time of Rb-Sr isotopic re-setting in Wisconsin and perhaps folding of the Baraboo Quartzite (Van Schmus, 1980).

Now that the post-1760 Ma age of the Baraboo Quartzite has been firmly established, based on the new evidence from drill core 613, the deposition of red, mature, fluvial quartz arenites, which are regionally extensive and up to 2,000 meters thick, can be viewed as the result of cratonic cooling and subsidence, following the cessation of 1760 Ma granite-rhyolite magmatism. The time of folding and metamorphism of the Baraboo Quartzite is still unclear; it could have been at 1650 Ma, but recently obtained isotopic evidence indicates the existence of a metamorphic event at ~1720 Ma in the southern Lake Superior region (Van Wyck, 1995). Thus, the Baraboo-Barron-Sioux triad could have been deposited in either of the intervals, 1760-1720 Ma, or 1720-1650 Ma. In either case, ample time, on the order of 40 or 70 Ma, would have been available for development of mature quartz sandstones, especially in response to lateritic weathering, as indicated by aluminous minerals in the Baraboo Quartzite.

The Baraboo interval is a valid and useful concept for interpreting the mid-Proterozoic evolution of the Lake Superior region, but it applies only to post-1760 Ma quartzites. Treating all Proterozoic quartzites in Wisconsin as correlative leads to serious misinterpretations of the Baraboo Quartzite, in particular, and of the Proterozoic evolution of the Lake Superior region, in general.

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THE LATENT MAGMATIC STAGE OF THE MIDCONTINENT RIFT: A PERIOD OF MAGMATIC UNDERPLATING AND MELTING OF THE LOWER CRUST

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Field studies, seismic and gravity data, U-Pb zircon dating, and geochemical studies of volcanic and intrusive rock suites around the Lake Superior basin show that the Midcontinent rift (MCR) evolved in several distinct magmatic stages between 1109 and 1086 Ma (1-4). Most recently, a period of substantially reduced volcanism and a shift to more intermediate to felsic magma compositions has been identified between 1107 and 1100 Ma—an interval we refer to as the latent magmatic stage (Fig. 1). Overall, MCR magmatism resulted from an anomalously hot mantle plume emplaced at the base of the lithosphere at about 1109 Ma (5). The most obvious aspect of this magmatism is the large volume (over 2 million km³) of mostly basaltic volcanic rock that accumulated in the central rift graben to thicknesses of up to 20 km (1). Less obvious, but equally significant is a comparable volume of mafic magma that intruded and underplated the crust beneath the Lake Superior region (6,7). We present evidence here that suggests a contemporaneous if not a causal relationship between the latent magmatic stage, magmatic underplating, and lower crustal melting.

The first hint of a latent magmatic stage was recognition of a hiatus in mafic intrusive activity in the Duluth Complex between 1107 Ma and 1099 Ma (8). More recent U-Pb dating of the North Shore Volcanic Group (9) and the Powder Mill Group (10) has revealed a decrease in volcanic activity over this same period. Volcanic rocks occurring within and adjacent to both these low production intervals are mixed rhyolite, andesite, and evolved basalt (4, 11). Insufficient dating has been conducted to determine if a similar decrease in basaltic volcanism is present in the Osler and Mamainse Point volcanics suites. However, it is noteworthy that the Agate Point rhyolite, which separates the upper and central suite of Osler Group (12), yields an age of 1105±2 Ma (9). At Mamainse Point, abundant felsic flows and intrusions have been mapped below the 420-m-thick, polymict Great Conglomerate (13), which presumably signifies a prolonged hiatus of volcanic activity. Further evidence that felsic volcanism predominated during an overall diminution of volcanic activity comes from the preponderance of rhyolite clasts in the Copper Harbor Conglomerate and their age of 1104±2 Ma (14).

We propose that the latent magmatic stage represents a period of reduced extension coupled with extensive magmatic underplating and melting of the lower crust. If the rate and intensity of extension in the MCR was largely controlled by external stresses imparted by contemporaneous Grenvillian tectonism (15), then ponding of magmas at the crust-mantle interface was likely a passive response to decreased tensile (or perhaps compressive) stresses in the lithosphere. However, to the extent that lithospheric thinning and extension was driven by the buoyancy and thermal energy of the mantle plume (16), then perhaps magma underplating actually caused diminished extension of the crust by delaminating and structurally decoupling it from the lithospheric mantle. In either case, underplating was probably instigated by the heating and anatexis of the lower crust caused by the passage of the earliest mantle-derived magmas coupled with heating from the rising plume. The creation of felsic melts and an increasingly ductile lower crust would have created density and rheologic barriers to impede the passage of mafic melts and promote their ponding (17). Once initiated, mafic magma chambers would have continued to expand as additional rising mantle melts became trapped and triggered more widespread melting of the lower crust. At the peak of the latent stage, the lower crust may have been largely impermeable to mafic magmas. Although the resumption of volcanic activity at about 1102-1100 Ma (earlier near the axis of the rift) may have been externally triggered by increased extension of the crust, it seems also possible that density cleansing of the lower crust caused by the upward migration of low density felsic melts and perhaps thinning of the ductile lower crust concomitant with magma underplating may have played important roles in allowing basaltic magmas to emerge from deep crustal magma chambers.

The formation of large magma chambers in the lower crust helps explain many of the lithologic, and geochemical characteristics that are generally common to all volcanic suites formed during the latent magmatic stage as well as magmatism leading up to and following it (Fig. 1). Some of the more cogent features are:

- **Felsic magmatism**—The bulk and isotopic composition of rhyolite flows and their greater abundance relative to flows of intermediate composition indicates that many if not most were generated from partial melting of crustal sources rather than as differentiates of mafic magmas (18, 19). The greater concentration of felsic lavas in stratigraphic intervals straddling the latent stage (Fig. 1) is consistent with it being a period of lower crustal melting coupled with diminished basaltic volcanism. However, the moderately negative $\epsilon_{\text{Nd}(1100)}$ (~ -4) of felsic lavas in the lower part of the NSVG (Fig. 1) is difficult to explain by melting of Archean lower crust, which should have $\epsilon_{\text{Nd}(1100)} = -12$ to -17 (18, 19). Although this may indicate mixing of Keweenawan felsic differentiates with Archean crustal melts (19), an intriguing alternative explanation is that the lower crust is composed of Early Proterozoic rocks ($\epsilon_{\text{Nd}(1100)} = -4$ to -12). The persistence of felsic volcanism with varied $\epsilon_{\text{Nd}(1100)}$ well into the middle of main stage magmatism (~ 1096 Ma) may reflect melting of the base of the volcanic pile producing some of the high $\epsilon_{\text{Nd}(1100)}$ (18) or melting of progressively higher (Archean) crustal levels with low $\epsilon_{\text{Nd}(1100)}$.
- **Evolved basalt and intermediate lavas**—Basalt in all stratigraphic intervals straddling the latent stage displays a broad, but overall low range of $mg\#$ - a general indicator of the differentiated composition of mafic magmas (Fig. 1). Moreover, intermediate lava compositions that were probably generated by differentiation of mafic magmas (e.g., basaltic andesite, andesite and icelandite) are highly concentrated within these same intervals in the Powder Mill Group (4) and North Shore Volcanic Group (11). This concentration of evolved lava compositions is consistent with prolonged crustal staging of mantle-derived magmas leading to greater degrees of differentiation during this period. The broad and commonly erratic range of compositions erupted prior to and following the latent stage (e.g., 21) suggests that multiple, open-system staging chambers existed throughout the lower crust.
- **Contaminated basalt**—Trace element (e.g. Th/Yb) and Nd isotope geochemistry of basalts (Fig. 1) suggest that crustal contamination was most prevalent in the period leading up to the latent magmatic stage. The greatest potential for interaction between mantle melts and continental crust would be expected to occur during the initial development of lower crustal magma chambers. Once established, crystallization and continued inflation of such chambers would have insulated them from further contamination and diluted the initial contamination.
- **Plagioclase crystal mush**—Leucocratic intrusions of the Mellen Complex formed at 1102 Ma (10), the anorthositic series of the Duluth Complex at 1099 Ma (9), and the widespread occurrence of plagioclase-phyric lava flows (p, Fig. 1) indicate that plagioclase-enriched basaltic magmas were commonly emplaced into the upper crust between 1108 and 1096 Ma. Such plagioclase crystal mushes were likely generated in lower crustal magma chambers where high pressures would have promoted the flotation of plagioclase (20). An implied consequence of this flotation is the formation of anorthositic roof zones in these deep chambers. Such roof-zone material was the likely source of anorthosite inclusions found in the Beaver Bay Complex.

The interpretation of the latent magmatic stage as a period of extensive magmatic underplating and crustal melting carries significant implications for the geodynamic and magmatic evolution of the MCR which need to be more fully explored. Whether underplating was the cause or effect of reduced crustal extension and the development of the latent magmatic stage hinges on the larger question of what drives continental rifting. Future petrologic studies should be directed at evaluating the extent to which open-system crystallization differentiation of mantle-derived magmas under high pressures (7-10 Kb) can account for the compositional range of MCR lavas and at more precisely determining the sources of felsic magmas. In addition, more high precision U-Pb ages are necessary to verify the existence and duration of the latent magmatic stage in all sequences and to better establish correlation between Mamainse Point lavas and volcanic sequences in the western Lake Superior region.

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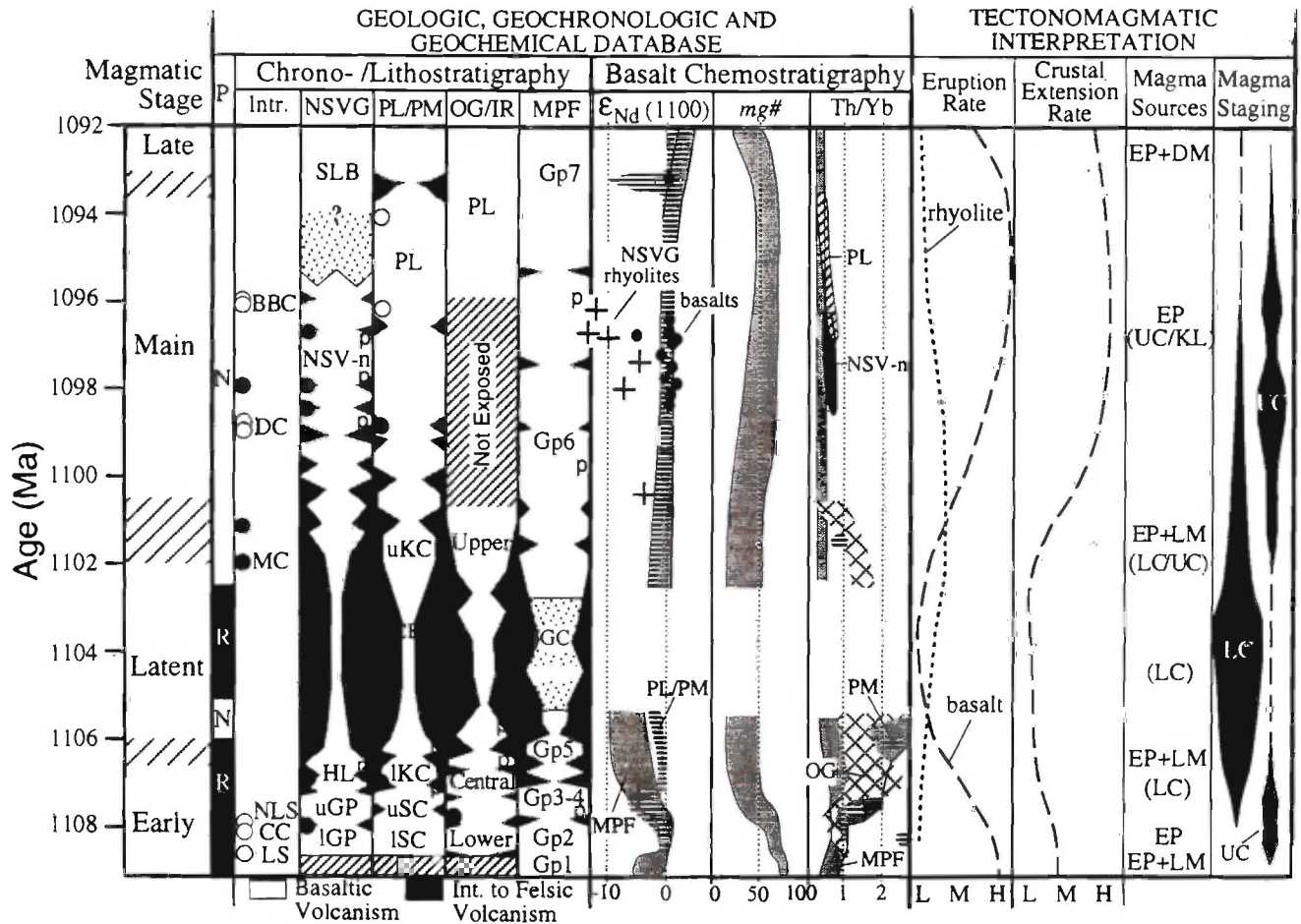


FIGURE 1. Correlation of units, summary of lithologic and chemical characteristics, and interpretations of the tectonomagmatic evolution during magmatic stages of the Midcontinent rift. Intervals of Normal and Reversed magnetic polarity indicated (P). Relative abundances of basaltic and felsic volcanics schematically portrayed and general locations of plagioclase porphyritic flows (p) noted for the major volcanic suites—NSVG-North Shore Volcanic Group(11); PL/PM- Portage Lake Volcanics and Powder Mill Group (4); OG/IR- Osler Volcanic Group and PL on Isle Royale (12); MPF- Mamainse Point Formation(2,13). Subdivisions of volcanic suites are NSVG: IGP/uGP, HL, NSV-n, SLB-lower/upper Grand Portage lavas, Hovland lavas, NSVG-normal polarity, and Schroeder-Lutsen basalts of (11); PM: ISC/uSC, IKC/uKC- lower/upper Seimens Creek lavas and lower /upper Kallander Creek volcanics of (4); OG: lower, central and upper suites of (12); MPF: Groups 1-7 of (2); CHC-Copper Harbor Conglomerate; GC- Great Conglomerate. Intrusive rock units are LS- Logan Sills, CC- Coldwell Complex, NLS- Nathan's Layered Series, MC- Mellen Complex, DC- Duluth Complex, BBC- Beaver Bay Complex. Average U-Pb ages for various volcanic and intrusive rocks indicated by filled (felsic) and open (mafic) circles; data from (8), (9), (10), and sources listed therein. $\epsilon_{Nd(1100)}$ data from MPF (2), PL/PM (4), NSVG rhyolite (19), NSVG basalt (21). $mg\#$ ($= MgO/(MgO+FeO)*100$) of common range displayed by basalt in all volcanic suites (2,4,11,12,21, 22, 23). Th/Yb data from MPF (2), PM (4), OG (12), NSV-n (21), PL (22, 23). Relative eruption and extension rates (Low, Medium, High) interpreted from thicknesses of volcanic suite relative to period of eruption. Magma sources for basaltic composition: EP- enriched plume, LM- lithospheric mantle, DM- depleted asthenospheric mantle (modified from (2) and (3)). Magma sources for felsic compositions in parentheses: LC- lower crust, UC - upper crust, KL - Keweenaw lavas. Interpretations of relative volumes of magma staging in the lower crust (LC) and upper crust (UC) denoted by relative widths of curves.

PRELIMINARY SEDIMENTOLOGIC AND PETROLOGIC ANALYSIS OF THE EARLY PROTEROZOIC MAHNOMEN FORMATION (NORTH RANGE GROUP) EAST-CENTRAL MINNESOTA

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The term North Range Group was proposed by Southwick et al. (1988) for Early Proterozoic strata sandwiched between the underlying Mille Lacs Group and overlying Animikie Group on the North Cuyuna range. As described by Schmidt (1963), the group consists of a lower siltstone-shale sequence—the Mahnomen Formation; an intermediate and dominantly Fe + Mn-rich unit—the Trommald Formation, and a upper graywacke-shale sequence—the Rabbit Lake Formation. Much of the Trommald Formation contains evidence of hydrothermal or fumarolic processes; little is known however, about the enclosing epiclastic strata. To clarify the sedimentary history of the Mahnomen Formation, we have re-examined more than 320 m of continuous core first described by Grout and Wolff (1955) from four sites across the range. However, our work must be considered preliminary, for Schmidt has estimated that the Mahnomen is at least 600 m thick.

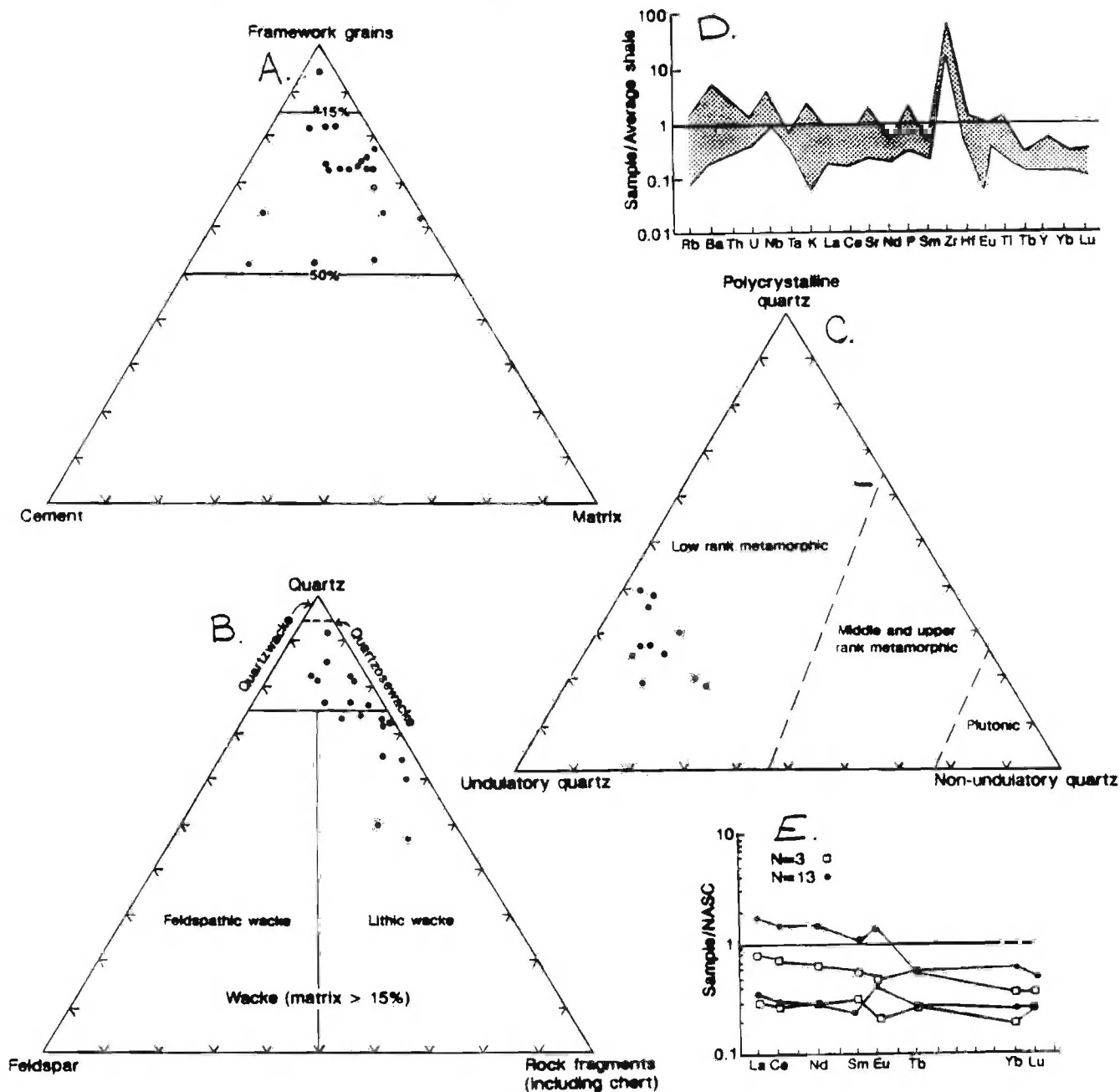
As much as 90 percent of the Mahnomen core consists of laminated to very thin-bedded claystone, mudstone or shale, and siltstone. Claystone—now mainly clay-size sericite $\pm$ chlorite—contains <5 modal percent, silt-size quartz. Mudstone contains from ≤ 25 percent silt-size quartz scattered more or less randomly through the matrix, whereas in shale similar amounts of quartz define a fissile layering. Siltstone contains 25-80 modal percent silt, plus some fine sand-size quartz $\pm$ trace amounts of chert or iron-formation. Some beds are calcareous with 20 modal percent calcite, whereas others contain >50 modal percent, constituting limestone of several varieties. The fine-grained rocks define upward-fining sequences 5-20 m thick, where siltstone predominates in the lower parts and claystone and mudstone or shale predominate in the upper parts. Bedding is straight and regular but interrupted in places by synsedimentary faults, overturned folds, and other evidence of slumping. Many siltstone beds have scoured lower surfaces, are graded, and are topped by climbing-ripple laminae. Compaction features such as flame structures and load casts(?) are common.

Contrary to earlier published descriptions, sandstone is a rare component comprising no more than 5 percent of the described cores. It occurs in generally structureless to vaguely graded and layered beds 2-3 cm to 1 meter thick; they are interspersed throughout the cores. Most beds are fine- to medium-grained, quartzose or lithic wackes having >15 modal percent matrix (mainly chlorite $\pm$ sericite). Other constituents (Fig. A) include 2-29 modal percent cement (possibly ankerite $\pm$ hematite) and 52-94 modal percent framework grains. Quartz (50-92 modal percent), dominates the framework grains (Fig. B), especially in coarser grained samples, followed by rock fragments of metasedimentary origin (9-43 modal percent) and feldspar, mainly plagioclase (5-15 modal percent). These modal abundances are misleading, however, for there is considerable textural evidence that much of the matrix has been formed by the breakdown of unstable metasedimentary rock fragments. Nonetheless, the Mahnomen is clearly a second-cycle sequence derived from an older metasedimentary provenance—most likely the underlying Mille Lacs Group, a possible provenance also suggested by quartz types that point to a "low rank metamorphic source" (Fig. C).

Major, minor, and trace-element compositions (Fig. D) are similar to those of an average shale, where plagioclase and, consequently, sodium are generally lacking and where potassium is associated with sericite. REE compositions (Fig. E) are broadly consistent with a cratonic source, show slight depletion in HREE and are marked by flat Ce anomalies and mostly positive Eu anomalies. However, a few samples have low REE totals and negative Eu anomalies; they may contain a volcanogenic component. Beds of volcanogenic material as thick

as 10 cm, are mainly ash-fall tuff. They have been recognized and described from elsewhere on the range by Melcher et al. (1996).

The North Range Group has been folded at least twice and metamorphosed to the greenschist facies. As such it is part of the Penokean fold-and-thrust belt. Hemming et al. (1993) used Sm-Nd techniques to show that detritus in the Mahnomen were derived from an Archean provenance. Morey and Southwick (1995) used that information to suggest that the Mahnomen was deposited on an evolving continental margin early in the tectonic history of the Penokean orogen. However, because the Mahnomen is a second-cycle sand, such a suggestion may no longer be applicable to the tectonic evolution of the Penokean orogen.



MISSISSIPPI VALLEY-TYPE MINERALIZATION IN THE FOX RIVER VALLEY, EASTERN WISCONSIN

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Regional NURE (National Uranium Resource Evaluation Program) geochemical data suggest that anomalous concentrations of arsenic and other mineral exploration path-finder elements are present in the area southwest of Green Bay, Wisconsin where the Sinipee, Ancell and Prairie du Chien Groups are the uppermost bedrock units. In addition, fluorine levels in groundwater have long been known to be high in the Fox River valley between Green Bay and Appleton, where fluorite and other Mississippi Valley-type minerals are reported to be present in well cuttings from the Sinipee Group.

Areas of significantly elevated values occupy northwestern Outagamie county and adjacent areas. A clearly defined nickel province that spatially corresponds to the arsenic province suggest that a polymetallic (As, Co, Mo, Ni, Th, V) hydrogeochemical province exists in eastern Wisconsin and may relate to documented faults (Mudrey and Bradbury, 1992). The geology differs from the better documented five-element (Ni-Co-As-Ag-Bi) veins (Kissin, 1993) by being carbonate hosted rather than shale or volcanic hosted, but are similar in essential mineralogy and elements.

Economic concentrations of Mississippi Valley-type mineralization have not been found in Wisconsin outside of Grant, Iowa, and Lafayette Counties, but geologic logs of 16 mineral exploration holes and more than 600 water wells in eastern Wisconsin contain reports of minor mineralization. In addition, more than 100 occurrences of sulfide mineral have been reported from outcrops and quarries throughout southern and eastern Wisconsin (Brown and Maass, 1992). A fairly continuous horizon of sulfide mineralization has been observed in quarries and drill cores from Kenosha to Green Bay. Mineralization within this horizon infills intergranular and moldic porosity from 2 m above to 6 m below the base of the middle-Ordovician Platteville Formation, cross-cutting bedding and strata of varying lithologies that immediately underlie the Platteville Formation (Simo, Freiberg, and Freiberg, in press).]

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Metamorphism of Chengwatana Volcanic Group Near Taylors Falls and From Osseo Core

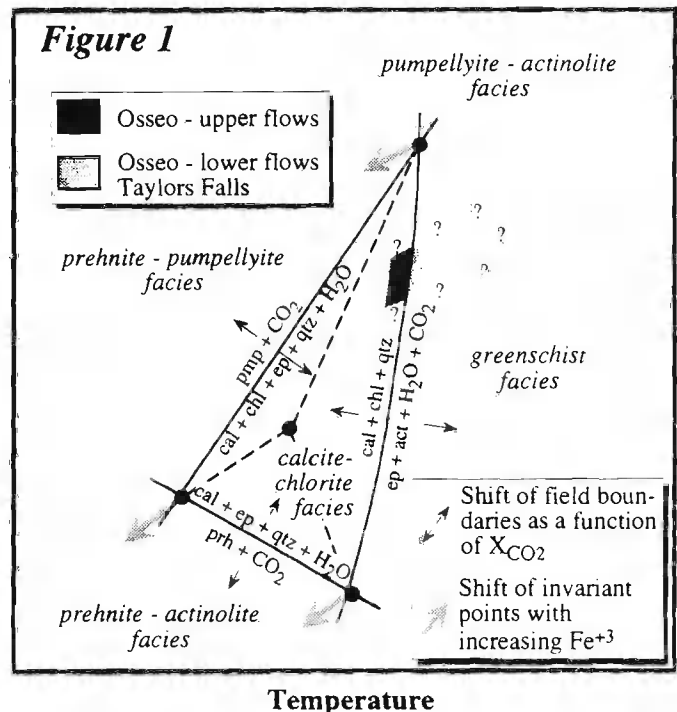
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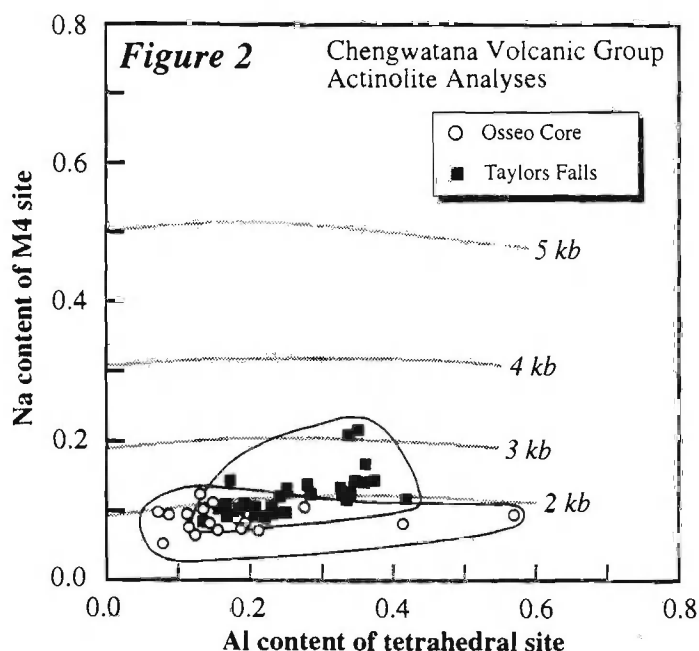
The southernmost exposed flows from the 1100 Ma Midcontinent rift of North America comprise the Chengwatana Volcanic Group, a sequence of more than seventy mafic flows exposed in the Taylors Falls-Interstate State Park region (>2800 meters thick) on the Minnesota-Wisconsin border. A core at Osseo (63 km SW of the exposures) sampled 980 meters of more than fifty flows of Chengwatana basalt 230 meters below the surface. Flows in both sequences are typically interlayered with sedimentary breccia. Stratigraphic correlation with other volcanic sequences of the North Shore region of the rift are complicated by faulting.

Volcanic flows from both regions have similar primary igneous mineral assemblages (plagioclase + clinopyroxene + Fe-Ti oxides) and display a variety of igneous textures (ophitic, sub-ophitic, ophimottled, intergranular, intersertal, plagioclase phyric, and seriate). The textures indicate a crystallization sequence of plag → cpx → oxides typical of tholeiitic basalt. Single flows commonly exhibit more than one texture; ophitic texture is more common in flow interiors where the cpx presumably had sufficient time to crystallize during slow cooling whereas intersertal and ophimottled textures are more common at flow tops where more rapid cooling prevented the formation of large cpx crystals. Osseo flows have a higher proportion of ophitic texture and on average are coarser grained than Taylors Falls flows.

The metamorphic environment of the Chengwatana volcanics is best modelled by the CaO-MgO-Al₂O₃-Fe₂O₃-SiO₂-H₂O-CO₂ (CMAFSH-CO₂) basaltic system determined by Liou et al. (1985) and Cho and Liou (1987). The equilibrium metamorphic mineral assemblage of the top 670 meters of the Osseo core consists of calcite + epidote + chlorite + quartz + albite + oxides ± white mica. Toward the bottom of the drill core, the occurrence of calcite is limited to veins and amygdulites whereas actinolite becomes prominent in the groundmass. These assemblages, defined by the reaction $\text{cal} + \text{chl} + \text{qtz} = \text{ep} + \text{act} + \text{H}_2\text{O} + \text{CO}_2$, are consistent with the transition from *calcite-chlorite facies* to *greenschist facies* (Fig. 1). The entire section at Taylors Falls displays the mineral assemblage: actinolite + epidote + chlorite + quartz + albite + oxides ± white mica.

The stability region of the *calcite-chlorite facies* in P/T space is constrained by the amounts of CO₂ and Fe³⁺ in the





system (Fig. 1). Currently there are no geothermometers which can be applied to this system. However, the Na-content of the M4-site (NaM4) of actinolite in the presence of chlorite, epidote, and quartz is a useful geobarometer (Brown, 1977). SEM-EDS analyses of actinolite in the Osseo core contain less NaM4 than actinolite from the Taylors Falls region suggesting that the Osseo flows were metamorphosed at slightly lower pressure (Fig. 2).

The temperature conditions during metamorphism of the Chengwatana flows at Taylors Falls are constrained by the presence of actinolite and epidote (Fig. 1), by the absence of co-existing prehnite and pumpellyite, and by the lack of hornblende coexisting with epidote, chlorite, actinolite,

and quartz. Epidote, rather than clinozoisite, is present in the Chengwatana flows due to the high-iron content of the protolith. At a pressure of ≈ 2.5 kbar, the equilibrium mineral assemblages indicate metamorphic temperatures of 325 - 375°C. Assuming a peak metamorphic temperature of 350°C and burial depth of 7.5 km, the metamorphic data from the Chengwatana flows imply a geothermal gradient of approximately 45-50°C/km within this portion of the midcontinent rift. Similar results have been determined elsewhere in the midcontinent rift and in the Kenya Rift of east Africa.

The change from *calcite-chlorite* to *greenschist facies* in the Osseo core, the ubiquitous presence of *greenschist facies* in the Taylors Falls exposures, and the lower NaM4 content of actinolite in the Osseo core imply that the Chengwatana flows sampled by the Osseo drill core were not buried as deeply as the flows exposed at Taylors Falls. If the flow sequences in these two regions are part of the same volcanic plateau-segment of the midcontinent rift, and if these regions are not separated by structures with large offsets, the flows sampled in the Osseo core might be stratigraphically younger than those of the Taylors Falls region.

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A CONTINUUM OF STRESS-STRAIN FIELDS (2.0-1.0 Ga) ALONG THE NORTHERN MARGIN OF THE KEWEENAW PROVINCE, ONTARIO, CANADA

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The structural evolution of the Keweenaw rift (1.1 Ga) is well constrained for much of the exposed southern arm, and involved early extensional faulting and magmatic activity, followed by closure of the rift along the same boundary faults by thrust motion (e.g., Douglas and Keweenaw-Lake Owen thrusts) at ~1.06 Ga (Bornhorst et al., 1987; Cannon, 1994). This structural scenario is complimented by studies of the mechanical twinning strains preserved in calcites (amygdules, veins, cements, cements in clastic dikes, and overlying Paleozoic limestones) throughout the region which record syn-rifting subhorizontal shortening parallel to the rift, followed by rift-normal subhorizontal shortening related to thrust closure of the rift (Craddock et al., in press). The other portions of the Keweenaw rift-triple junction are unexposed (gravity, magnetic anomaly) beneath the Michigan basin or poorly constrained north of Lake Superior.

In this study we have characterized the structural relations of calcite twinning patterns to the "failed third arm" portion of the rift system between the Kapuskasing suture, the Coldwell alkali complex and the Nipigon Embayment over the interval ~2.0-1.0 Ga. Our results (Table, Figs. 1-3) suggest that the orientation of the regional compressive stress (or shortening strain) field was subhorizontal and N-S prior to rifting, subhorizontal and rift-parallel during rifting, and subhorizontal and rift-normal as the rift closed by thrusting.

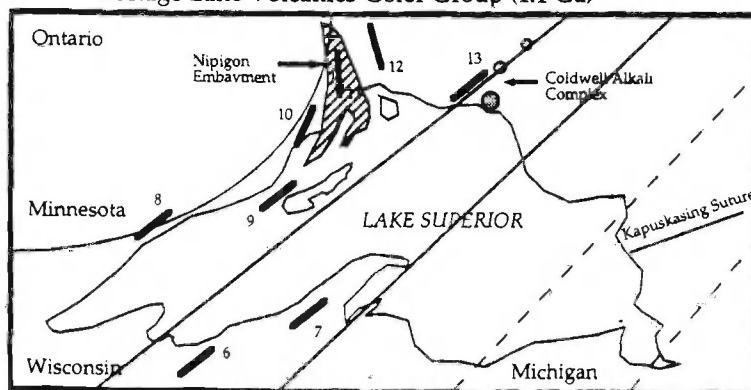
Sample	e1(%)	e1(tr & pl)	NEVs (%)	Calcite type	~Age (Ga)
1	-7.7	340°, 0°	16	Dike margin vein	2.0
2	-5.5	170°, 8°	0	Dike Margin vein	2.0
3	-2.1	170°, 5°	0	Sibley Limestone	1.54
4	-4.5	16°, 5°	21	Sibley Limestone	1.54
5	-5.9	164°, 0°	12	Limestone	~2.0
6	-9.8	50°, 0°	30	Basalt amygdale	1.1
7	-3.4	41°, 0°	28	Basalt amygdale	1.1
8	-3.3	52°, 0°	37	Basalt amygdale	1.1
9	-0.2	55°, 0°	0	Basalt amygdale	1.1
10	-0.8	20, 0	47	Vein	~1.1
11	-0.7	355°, 20°	28	Vein	~1.1
12	-2.4	76°, 8°	5	Vein	~1.1
13	-1.6	56°, 17°	0	Carbonatite	~1.1
14	-1.2	150°, 0°	26	Vein	<1.06
15	-6.7	171°, 0°	30	Vein	<1.06
16	-1.9	162°, 0°	14	Vein	<1.06
17	-0.4	165°, 0°	13	Vein-amygdale	<1.06
18	-0.2	170°, 0°	33	Vein-amygdale	<1.06
19	-0.2	170°, 0°	0	Vein	<1.06
20	-0.2	168°, 0°	8	Vein	<1.06
21	-0.6	270°, 5°	7	Vein	<1.06
22	-2.9	160°, 7°	100	Carbonatite	~1.1
23	-4.9	253°, 0°	0	Vein	<1.06
24	-0.4	170°, 5°	20	Vein	<1.06
25	-0.4	355°, 12°	30	Vein	<1.06
26	-4.9	300°, 7°	16	Lamprophyre	<1.06

Kenora-Kabetogama and Sibley Group (2.0-1.5 Ga)

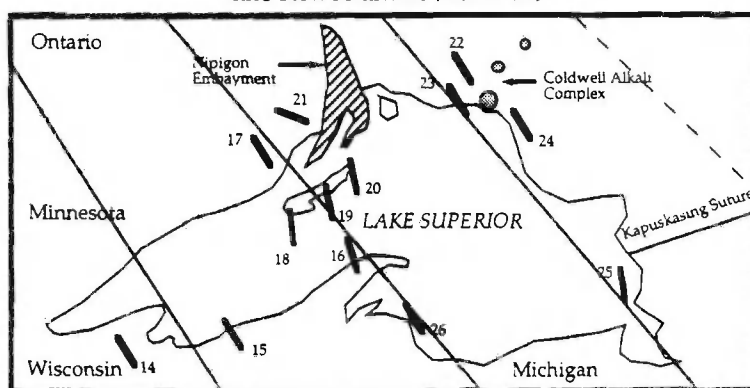


Figures 1-3: Regional summary plots of calcite twinning data (see Table) for time increments between ~2.0-1.0 Ga. Solid, bold lines are calcite shortening strain axes, with sample number (see Table). Regional compressive stress (σ) or shortening strain (E) fields are inferred from these data for each time period. Lake Superior is used as a reference, with no attempt being made to include plate or fault boundaries that were active during the billion years of Earth history involved.

Portage Lake Volcanics-Osler Group (1.1 Ga)



Late Keweenaw (<1.06 Ga)



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**CYCLIC TIDAL LAMINATIONS IN THE EARLY PROTEROZOIC POKEGAMA
FORMATION: DIGITAL IMAGE ANALYSIS AND COMPUTER MODELING**

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Evidence of the diurnal inequality operating in Early Proterozoic time is apparently recorded in a sequence of alternating thicker and thinner clastic silt laminae identified in the lower member of the Pokegama Formation of northern Minnesota. The sequence of apparently semidiurnal laminae is present in a silty lens-shaped bed of the argillaceous member, interpreted to be a small arm of a tidal channel system on the shore of the transgressive sea that occupied the ancient Animikie basin. The sequence consists of approximately 60 thin (0.1 - 1mm) silty laminae which tend to alternate in thickness, separated by thin mica-rich layers that exhibit a similar tendency. Such thick-thin patterns are expected to be generated by sediment transport in semidiurnal tidal environments, due to the alternating magnitudes of successive tidal velocity peaks in such environments (i.e., due to the tidal inequality). Thus, they may be used to support proposed tidal environments of deposition (cf. de Boer et al., 1989), and the sequence described here strongly supports the conclusion of Ojakangas (1983) that the Pokegama Formation is of tidal origin. It also suggests that the depositional site was probably non-equatorial in the Early Proterozoic. Hand specimens of the rhythmic sequence described above and other specimens displaying periodicities from the lower member of the formation have been slabbed, coated with oil to enhance detail, and photographed. The resulting images were then digitized and are currently under analysis using image-processing techniques.

In order to better understand the potential for extraction of information on the ancient lunar orbit from rhythmic tidal sedimentary sequences such as the one described here, a computer model has been created (Ojakangas et al., 1995) which generates synthetic tidal rhythmites from first principles, given arbitrary orbital elements of the earth and moon, and the latitude and longitude of a hypothetical location on the earth. Assuming equilibrium tide heights in the open ocean, tidal currents are generated in a hypothetical tidal channel linking the ocean to a tidal basin. The current in the channel, driven by the difference in water surface elevation between the basin and the open ocean, is computed assuming uniform turbulent flow according to Chezy's equation (cf. Dingman, 1984), and this flow is assumed to carry sediment at peak transport capacity as described by Yang and Stall (1976). Both mud and silt, transported in suspension, are deposited when the current speed drops below respective

critical values. The vertical eddy diffusion time is assumed short relative to the tidal cycle, so deposition is "instantaneous". The program successfully produces synthetic rhythmite sequences that closely resemble those of known rhythmites, such as those of the Late Proterozoic Elatina Formation described by Williams (1991). Because the tides are analytically generated, the significance of peaks in the power spectrum of the synthetic rhythmites can be understood. The conditions under which predetermined lunar orbital parameters can be retrieved from the corresponding synthetic rhythmites are under investigation with this model, as is the probable appearance and spectral content of very ancient rhythmites, as yet undiscovered. With this model as a tool, lamina sequences from the Pokegama Formation including the one described above are under analysis for possible clues to the ancient lunar orbit.

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TIDALITES OF EARLY PROTEROZOIC AGE IN THE WESTERN LAKE SUPERIOR REGION: MINNESOTA, WISCONSIN AND MICHIGAN

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The Palms Formation of the Gogebic Range of Michigan and the lithologically correlative Pokegama Formation of the Mesabi Range of Minnesota, both deposited upon Archean basement and both underlying major iron-formations, are terrigenous clastic units interpreted to be tidal deposits formed on the east-west-trending shoreline of a northward-transgressing Early Proterozoic sea (Ojakangas, 1983). The above four formations were either deposited on a stable shelf prior to the development of a foreland basin, or were deposited on the peripheral bulge of a foreland basin developing to the north of a major fold and thrust belt caused by the collision of the Wisconsin Magmatic Terrane with the continent. In either model, it can be assumed that the terrigenous clastics and the iron-formations form continuous, but diachronous, sheetlike deposits across the basin.

The well-exposed 150 m thick Palms Formation has a minor basal conglomerate, but is largely comprised of three major gradational facies which are as follows: 1. A thin-bedded argillaceous facies (lower member), 2. A dominant argillite-siltstone-sandstone facies (middle member) of thin-bedded intercalated lithologies and 3. a sandstone facies (upper member) of thick beds of parallel and planar cross-stratified sandstones. The middle member includes lenticular, wavy, flaser and parallel bedding and minor mudcracks. A total of 250 paleocurrent measurements, mostly cross-bedding but including sole marks, asymmetrical ripples, and trough axes, yields an overall bimodal-bipolar distribution. The modes are roughly parallel to the inferred shoreline.

The poorly exposed Pokegama Formation, as thick as 50 m, contains the same sequence of sedimentary facies as does the Palms. A few dozen scattered paleocurrent indicators form a polymodal paleocurrent plot, but detailed work on one long roadcut yielded 57 paleocurrent indicators, mostly paralleling the presumed shoreline of an embayment, but with one-fifth of them normal to the shoreline.

By the application of Walther's Law, the lateral relationships can be

interpreted. The conglomerate facies was locally present on the low-lying peneplaned surface prior to transgression of the sea. The argillite facies was the most proximal marine facies (i.e., upper tidal flat) resting upon conglomerate or basement Archean rocks. Seaward of the upper tidal flat was the middle tidal flat (argillite-siltstone-sandstone facies) and still further seaward was the lower tidal flat or subtidal environment (sandstone facies). As the sandstone facies is gradational with the overlying iron-formation, this places the site of the formation of iron minerals on the shelf, seaward of the terrigenous clastics.

Ignoring the basal conglomerates, which likely have a non-tidal origin, the Palms and the Pokegama are coarsening-upward sequences which are interpreted as products of a marine transgression. Such a model has been described by Reineck (1972) and Yeo and Risk (1981). Dutch tidal flats provide a modern analogy (De Jong, 1977).

Consistent with a tidal environment is the textural and mineralogic maturity of the sands (Swett et al., 1971; Balazs and Klein, 1972). Rounding and sorting is best in the sandstone facies where the energy was highest. However, first-cycle quartz sand eroded off of the vegetation-free, weathered and wind-swept adjacent peneplain may have already been well-rounded.

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Targeting Footwall Copper-PGE Deposits in the Duluth Complex Based on Sudbury Mining Camp Analogs

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Numerous workers have studied the genesis of the footwall Cu-PGE mineralization in the Sudbury Mining Camp. The Cu-PGE deposits are characterized by massive chalcopyrite veins, pods, and stringers with little (if any) alteration halos. The deposits are spatially associated with contact Ni-Cu ore deposits and extend hundreds of meters into the footwall rocks beneath these deposits. Vein grades of 30% Cu, 3% Ni, and 0.30 oz/st precious metals (Au, Ag, Pt, Pd) are typical. The most fundamental geologic process associated with the footwall deposits of the Sudbury Mining Camp is the migration of the ore metals from the Sudbury Igneous Complex into the footwall environment. Naldrett et al. (1982) suggested that the ores are attributable to the fractional crystallization of the sulfide liquid responsible for the formation of the contact Ni-Cu deposits. The footwall ores are believed to have formed by migration of the fractionated, copper-rich residual liquid away from the early crystallizing monosulphide solid solution (mss), into and along footwall structural zones. Subsequent geological studies have refined this early ore deposit model.

The targeting of mineralization beneath the Duluth Complex must first be based on the fundamental geologic process (migration of fractionated metals into the footwall) associated with deposit formation. The diagnostic criterion that indicates copper migration is the spatial variation of Cu-Ni grades and the lowering of the Cu/Ni ratio in the source rock. An approach is being developed to generate Cu-PGE exploration target areas in the footwall rocks beneath the Duluth Complex. Determination of copper depletion in mineralized basal troctolites of the Duluth Complex is the first step in the generation of footwall exploration targets. The likelihood of footwall Cu-PGE mineralization beneath the Duluth Complex is being modeled from visualizing the three-dimensional distribution of Cu-Ni in the Duluth Complex. The distribution of Cu-Ni in the Duluth Complex has been determined from a comprehensive compilation of all available drill hole chemistry. To date, the drill hole chemistry database (Cu, Ni, S, Au, Ag, Pt, Pd, Rh, Ir, Os, V, Cr, and Co) includes 61,560 assays (249,629 individual analyses) from 1435 drill holes (Table 2). Individual analyses are located in three-dimensions (UTM east, UTM north, elevation/feet above basal contact) from collar information and basal contact piercing points. Approximately 95% of all drill hole assays are currently in the database. Total assays for the areas in the Duluth Complex included in this study are given in Table 1.

The drill hole chemistry has been used to create weighted average (over 50 to 100ft zones) gridded image maps of Cu-Ni grades, Cu-equivalent, and Cu/Ni ratios for individual deposit areas. The maps reflect the distribution of the ore-metals in relation to the basal contact of the Duluth Complex. Eight zones have been used to define the distribution of ore-metals in the basal 500ft of the ten main Cu-Ni deposits of the Duluth Complex. The zones include 0-50', 50-100', 100-150', 150-200', 200-250', 250-300', 300-400' and 400-500' above the basal contact. The correlation of high Cu-Ni grades and low Cu/Ni ratios for individual zones has been determined by merging the Cu-Ni grade and Cu/Ni ratio data sets. An example of a composite image depicting modeled copper migration in the basal 500' of the Spruce Road Deposit is presented in Figure 1. Plotted within the image are dots representing locations of drill hole assay samples, beneath the Duluth Complex, in the underlying Giants Range Granite. A strong correlation exists between footwall drill hole assays with >1% Cu (sulfide veins ranging to 7.9% Cu) and the modeled copper migration in the overlying Duluth Complex. Based on preliminary data, this new method appears to be a good mineral exploration targeting method that could be used to predict favorable areas for hosting footwall deposits.

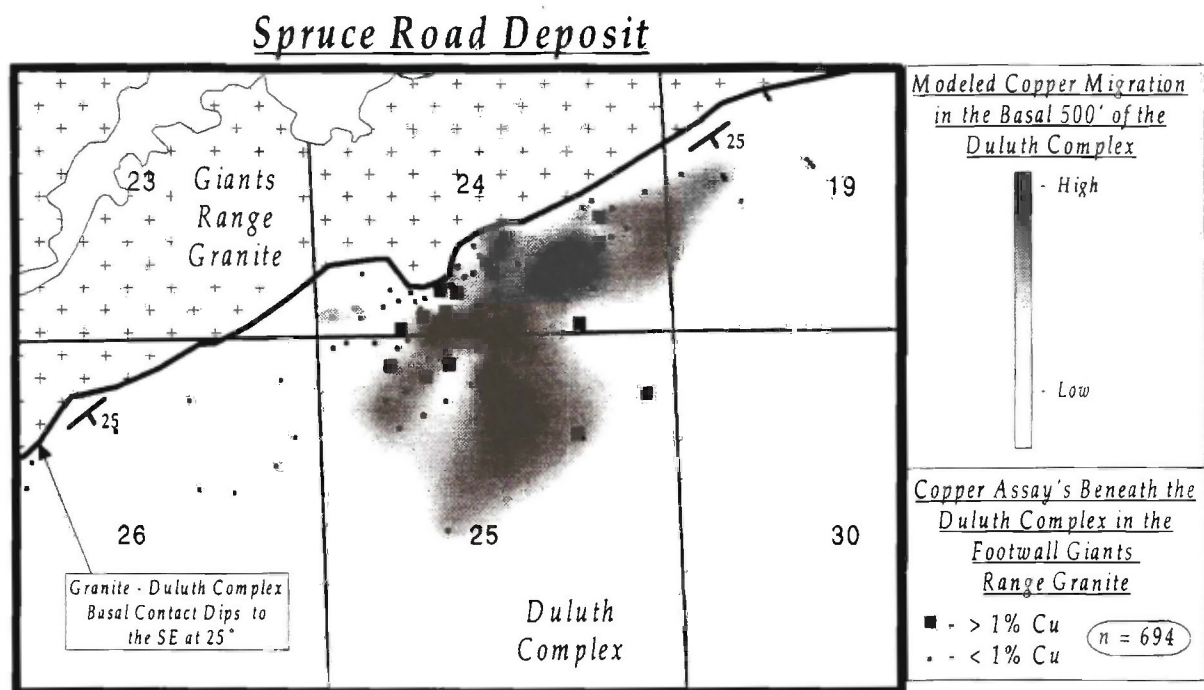


Figure 1. Correlation of modeled copper migration in the basal 500' of the Duluth Complex and known mineralization in the footwall Giants Range Granite, Spruce Road Deposit.

Table 1. Total deposit assays'

Deposit	#
Spruce Road	9281
Maturi	3246
Birch lake	958
Dunka Pit	4223
Serpentine	2000
Babbitt	30069
Dunka Road	2607
Wetlegs	1248
Wyman Creek	922
Waterhen	1813

Table 2. # of analyses for individual element

Element	#	Element	#
Copper	61,159	Palladium	5,897
Nickel	60,300	Rhodium	1,881
Sulfur	37,120	Iridium	203
Cu/Ni	60,266	Osmium	102
Gold	5,109	Vanadium	1,770
Silver	4,223	Chromium	2,799
Platinum	5,598	Cobalt	3,202

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PETROGENETIC RELATIONSHIPS BETWEEN APATITE-BEARING AND APATITE-DEFICIENT IRON OXIDE-RICH INTRUSIONS AND MASSIVE SULFIDE MINERALIZATION IN THE DULUTH COMPLEX, MN.

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Within the Duluth Complex oxide-rich, mafic to ultramafic intrusions (referred to as OUI by Severson and Hauck, 1990), occur as cross-cutting bodies and semi-conformable lenses. These bodies are rich in both ilmenite and titanomagnetite, and have been the subject of recent investigations by Jill Pasteris and students at Washington University, and Penny Morton at the University of Minnesota, Duluth. Although these oxide-rich bodies occur throughout the Complex there are some differences between those located in the southern portion of the Complex and those in the central and northern sections that have only recently been recognized. The best studied OUI in the central and northern portion of the Complex are characterized by low apatite content. In contrast, many of the OUI in the southern portion of the Complex, in particular the Boulder Lake area (Severson, 1995), are marked by abundant apatite. In at least a few areas true nelsonites (ilmenite-apatite rocks) have been found. These types of apatite-oxide occurrences are similar to cross-cutting bodies that are frequently found associated with massif-type anorthosites (e.g. Marcy, Grenville Province, Rogaland Complex). Accessory minerals in the nelsonites include biotite, zircon, Zn-rich spinel, and sulfides.

Massive sulfide mineralization at the Babbitt deposit is also cross-cutting in form, and is composed of essentially the same mineralogy as the apatite-oxide rocks, but obviously in different proportions. Euhedral apatite (locally up to 5%) occurs disseminated in the massive sulfides, along with biotite, Zn-rich hercynitic spinel, baddeleyite, ilmenite, and other oxides. We have previously proposed that the massive mineralization at Babbitt resulted from the emplacement of a volatile-rich, immiscible sulfide liquid. The same elements may be partitioned into an immiscible Fe-Ti-P-rich oxide liquid, and an origin similar to that of the massive sulfides is proposed. Sulfur isotopic values of the nelsonites (3-4‰) are distinctly different from those of the massive sulfides at Babbitt (10-14‰), and suggest that sulfur contamination of the nelsonites has not occurred.

The distinctly lower Cl and REE contents of the apatite from nelsonite and related rocks (Fig. 1) suggests that they either crystallized from a magma that had previously separated a Cl- and REE-rich fluid, or that had experienced prior crystallization of a Cl- and REE-compatible mineral. Both mechanisms are consistent with the premise that the apatite-rich OUI are genetically associated with highly evolved, residual melts. For example, Severson (1995) has described layered oxide-rich gabbros in the Boulder Lake area where apatite is a cumulus mineral. Just to the south in the Duluth Layered Series, Miller (1995) has also described five-phase cumulates where apatite is a primocryst mineral. In contrast, apatite is never a cumulus phase in the Partridge River (PRI) and South Kawishiwi (SKI) Intrusions in the central portion of the Complex. Apatite in the massive sulfide mineralization at Babbitt and that which occurs as an interstitial mineral in troctolites of the PRI (Fig. 1) are characterized by higher Cl and REE values relative to apatite in the apatite-rich OUI. The OUI in the central portion of the Complex are not as chemically evolved (e.g. olivine $Fo > 45$ vs. $Fo < 45$ in apatite-rich OUI), and appear to be related to interstitial melts of the PRI and SKI. In both types of OUI the paucity of feldspar component suggests that fractionation either through buoyant mineral accumulation or liquid immiscibility is an important genetic factor.

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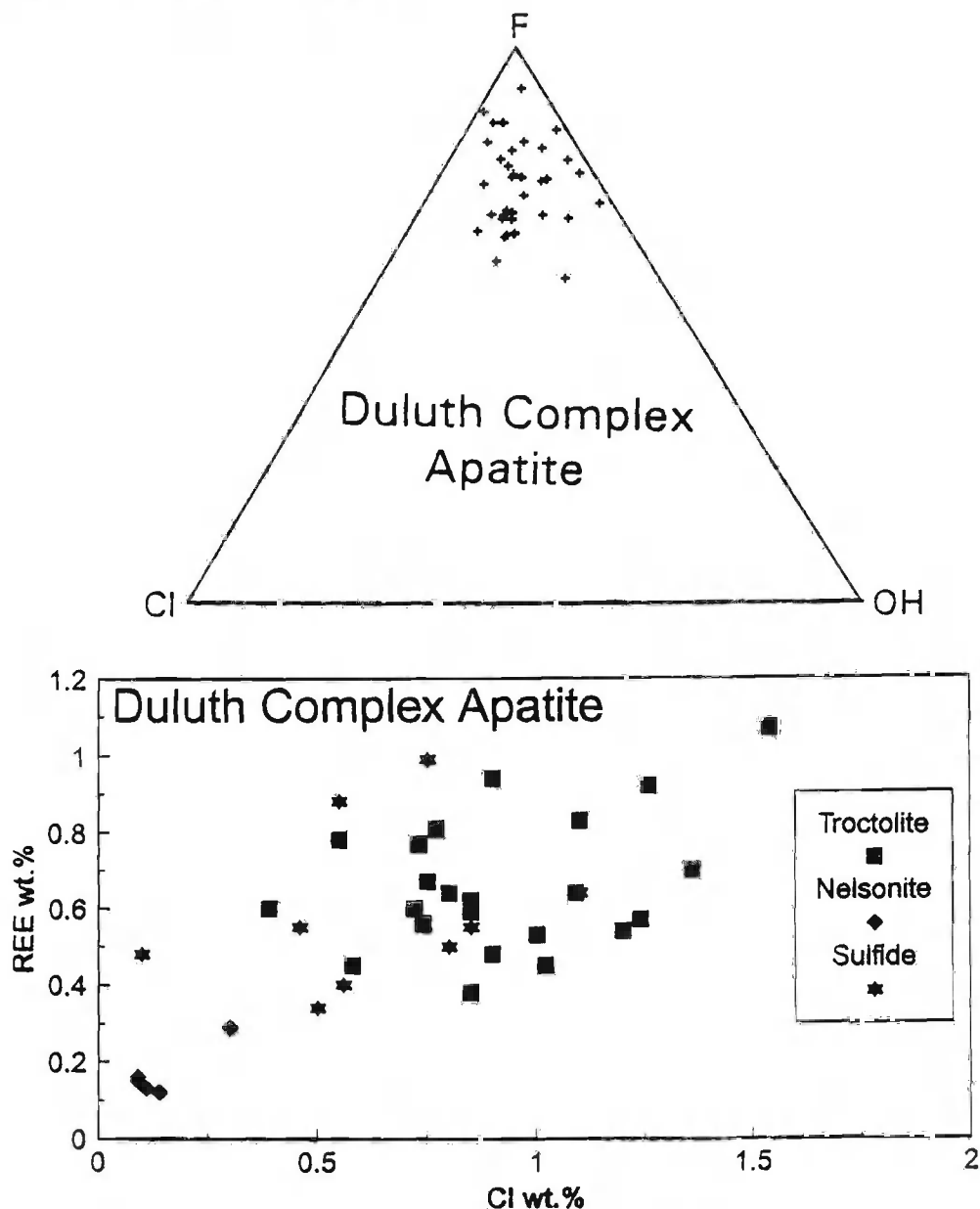


Figure 1. Compositional variations between apatite from apatite-rich OUI (here nelsonite), massive sulfide mineralization at Babbitt, and Fe-Ti-P-rich gabbroic to troctolitic rocks of the Partridge River Intrusion.

ULTRAMAFIC DIKE WITH MANTLE XENOLITHS: IMPLICATIONS TO DIAMOND EXPLORATION IN WAWA

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The Ontario Geological Survey completed 10 years of bedrock mapping in the Wawa area in 1988 under the supervision of R. Sage. When the Survey undertook a project to examine kimberlite occurrences in Ontario for diamond in 1993, R. Sage revisited the Wawa area to examine ultramafic dikes that displayed kimberlitic features. At the time of this visit Mr. Seymour Sears, Consulting Geologist, brought to the attention of the OGS that Mr. "Mickey" Clement had found what appeared to be diamonds in the area. The stones were confirmed to be diamond by the Royal Ontario Museum in 1993 which promptly launched the OGS into a sampling program for kimberlite indicator minerals (KIMs) under the direction of T. Morris. The alluvium sampling found abundant KIMs just south of Wawa prompting prospecting activity in the region. In August 1995 Mr. Terry Nicholson, Prospector, Wawa, encountered subcrop of what appeared to be a lamprophyre dike with mantle-derived xenoliths approximately 1.0 m wide trending 245 degrees, dipping 74 south in August 1995. Preliminary analysis of the mineralogy of the dike and some of the xenoliths has identified minerals comparable to those found in kimberlite.

Thin section, microprobe analysis and geochemical study of this dike are in progress within the OGS.

OCCURRENCE OF HIBBINGITE IN THE DULUTH COMPLEX, MINNESOTA, AND IN THE NORIL'SK COMPLEX AND KORSHUNOVSKOE IRON ORE DEPOSIT, RUSSIA

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Hibbingite, $\gamma\text{-Fe}_2(\text{OH})_3\text{Cl}$, first identified as an unnamed iron hydroxy chloride in the Deep Copper Zone of the Sudbury Complex (Springer, 1989), was characterized and named based on drill core samples from the Duluth Complex (Dahlberg, 1987, Dahlberg and Saini-Eidukat, 1991; Saini-Eidukat and others, 1994). Our investigations show that hibbingite is also found associated with platinum-group minerals in the Noril'sk Complex and with the Korshunovskoe iron ores of the southern Siberian platform. Hibbingite has also been documented by Buchwald (1995) as a terrestrial weathering product of Antarctic meteorites and of ancient iron archeological artifacts.

Hibbingite found in samples from the Noril'sk Complex differs from that of the Duluth Complex in containing significant kempite ($\text{Mn}_2(\text{OH})_3\text{Cl}$) component; in some cases it contains over 50 mol. % Mn. The grains, which are up to 0.6 mm in diameter, are associated with the platinum-group minerals froodite, cabriite, urvantsevite and with native silver in massive pentlandite–cubanite–chalcopyrite ore.

Hibbingite was also recognized in drill core from the Korshunovskoe iron ore deposit, located approximately 500 km to the NNE of Irkutsk city in the southern Siberian platform (Polozov and others, 1995). The sample in which it was found is composed of fine-grained magnetite ore associated with halite. Late pyrrhotite, calcite and chlorite crystals occur in numerous cavities; pyrrhotite may contain inclusions of halite. Hibbingite, hematite and silver grains are found in cavities in halite; the reddish-brown hibbingite grains usually occur as encrustations in the cavities. The size of hibbingite and hematite grains is up to 100 μm .

The grains from the Korshunovskoe deposit were analyzed in spring 1992, immediately after polished section preparation, and again in winter 1995-1996. The re-analysis established that with time the chlorine content of the grains decreased to approximately 6 wt.% concomitant with a small increase in iron. This agrees with re-analyses of Duluth Complex hibbingite and with the hypothesis that a breakdown product of hibbingite is akagenéite, $\text{Fe}_8(\text{O},\text{OH})_{16}\text{Cl}_{\leq 2}$, for which Cl is probably an essential component (Post and Buchwald, 1991).

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Clay minerals of the North Shore Volcanic Group and possible relationship to copper precipitation during alteration

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Several small occurrences of native copper with chalcopyrite, covellite, and galena are known in the Precambrian North Shore Volcanic Group, Minnesota. Whole rock values for copper in altered (flow tops and bottoms) and less altered flow units (massive flow interiors) range between 11 and 241 ppm, and Zn values between 49 and 167 ppm. Due to the general geochemical evolution of the series from a continental to an aborted rifting environment there is a general increase in the primary Cu content in the lava flow interiors from stratigraphically lower to higher flows (Basaltic Volcanism Project, 1982; Schmidt, 1990). Superimposed on this trend are secondary trends. In lower metamorphic grade flows, the massive flow interiors (dark square in Fig. 1a) show in general higher copper values than the flow tops and bottoms. This trend is reversed at the bottom of the series where the flows show alteration assemblages typical of beginning greenschist facies (prehnite-pumpellyite-chlorite or epidote-chlorite assemblages). Here, the altered flow tops and bottoms and the transition zones show higher Cu values than the massive flow interiors. At all stratigraphic levels, the highest copper values are observed in the transition zone to the massive flow interior, i. e. the near top or near bottom areas with clay minerals $\pm$ quartz - prehnite $\pm$ pumpellyite $\pm$ albite assemblages.

A similar trend is observed for zinc. It is only in the highest grade flow where the massive flow interior shows lower values than the other flow units (Fig. 1b). Again the transition zones to the massive flow interior (near bottom and near top) display the highest values.

In these metabasites clay minerals show a great variety in chemical composition as well as in structural type. Various types have been identified based on electron microprobe analysis, X-ray diffraction and deconvolution analysis. Smectites and mixed layer phyllosilicates are common in the flow tops of stratigraphically higher levels of lower metamorphic grade. Chlorites and corrensite are more common in flow tops of the stratigraphically lower part or higher grade metamorphic units (Schmidt, 1993 and Schmidt & Robinson, submitted). Smectites as well as mixed-layer minerals have also been identified in the massive flow interior of stratigraphically lower or higher grade flows.

Clay minerals have been isolated from the different morphological units and have been analyzed by XRF. They show varying contents of copper and zinc. In addition, selenium has been detected in smectite.

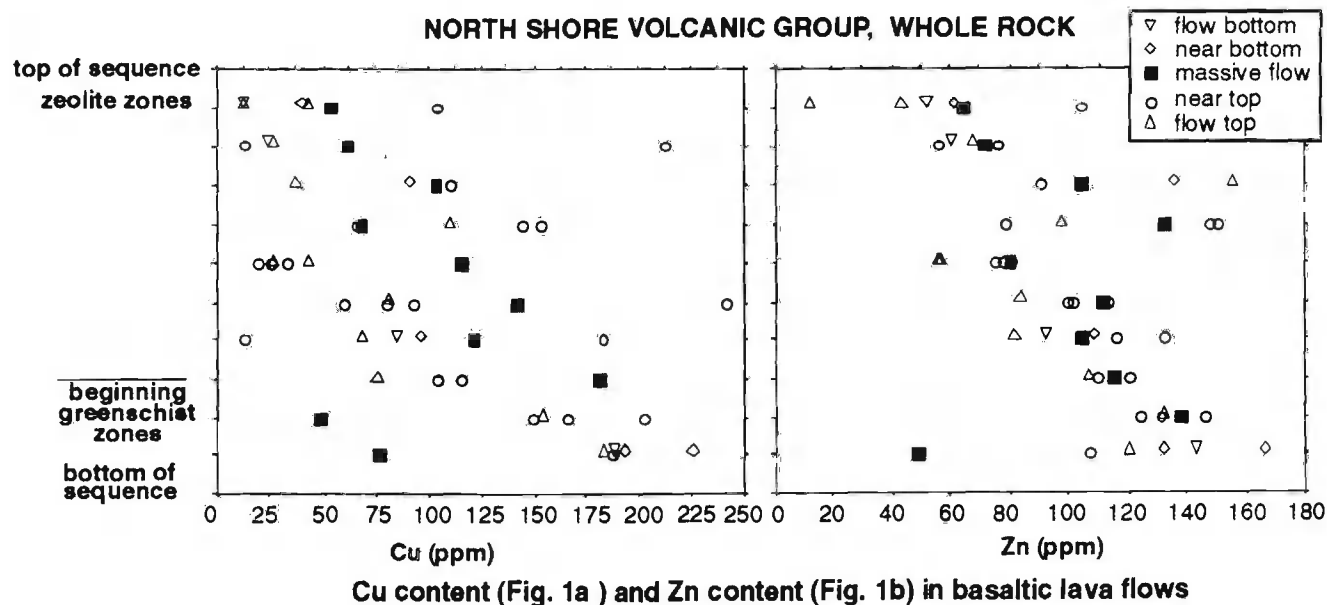
This suggests a close relationship of clay minerals to copper mineralization. Smectitic phases dominant in low grade metamorphic rock will not be stable under beginning greenschist conditions. They will break down and the copper will be released. Chlorite $\pm$ prehnite $\pm$ pumpellyite $\pm$ albite $\pm$ quartz assemblages will be stable and copper will be locally enriched in these assemblages.

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BASALTIC KOMATIITES AND ASSOCIATED ROCKS: IMPLICATIONS ON THE NATURE OF VOLCANISM IN PART OF THE SCHREIBER-HEMLO GREENSTONE BELT, NORTHWESTERN ONTARIO

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Well-preserved, basaltic komatiites have recently been discovered within a succession of subaqueous basalts and interflow sedimentary rocks of the Neoarchean Schreiber-Hemlo greenstone belt. Two, detailed sections consist of pillowed to massive, high-Mg tholeiitic basalt and basaltic komatiite. Individual flow sub-units, varying in thickness from 1 to 20 m, are intercalated and/or conformably stacked. "Crowded" and incipiently pillowed (~ 10% pillows) flows and autoclastic breccias comprise the bulk of the succession. Pillows range from small (≤ 30 cm), bun-shaped forms to large, mattress-shaped megapillows (>3 m). Broken pillow breccia and hyaloclastite occur between flow units and in interpillow spaces. These extrusive rocks are characteristically variolitic; varioles tend to coalesce in pillow cores, along selvages and along flow contacts.

A 9 m thick, composite, basaltic komatiite flow has been identified in the upper section. It consists of a massive, ultramafic base ($\text{MgO} \approx 20\%$) followed upwards by three, spinifex-textured flow units: (i) lower, foliated; (ii) coarse (≤ 8 cm), plate; and (iii) upper, randomly oriented. The MgO contents of these flow units range from 8% to 11%. Primary minerals have been replaced and pseudomorphed by metamorphic mineral assemblages consisting of tremolite-actinolite, serpentine, calcite, quartz and chlorite. Magnesian hornblende has replaced primary clinopyroxene that originally comprised the spinifex megacrysts and phenocrysts. In addition to these characteristic petrographic features, the major element chemistry is consistent with known basaltic komatiites.

Thin section petrography has revealed polygonal dendrite networks, skeletal / hollow-cored phenocrysts and devitrified glass. These textures, together with the various spinifex textures and tremendous variole development, suggest rapid chilling/quenching and undercooling of these basaltic lavas. The low vesicularity and disposition of the pillowed and brecciated flow units suggest deep water extrusion, on relatively flat depositional surfaces. Successive flow lobe or lava tube emplacement, with fluctuating lava levels, is supported by megapillow stacking and the presence of stacked lava shelves within pillows. The progression from (mega)pillow-dominated flows in the lower section, to incipiently pillowed and brecciated units in the upper, komatiitic section may indicate waning from high to lower effusion rates.

NORTHEASTERN MINNESOTA DULUTH COMPLEX MINERAL POTENTIAL

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Geologic maps of northeastern Minnesota show older assemblages of late Archean and early Proterozoic rocks truncated by a crescent shaped intrusive unit approximately 1.1 billion years old. The igneous rocks welled up in a rift of the earth's crust which runs northeasterly from Nebraska, through Iowa and up the eastern side of Minnesota. It then curves out into Lake Superior and runs southerly into Michigan. The rift is a major continental feature which is well defined by gravity and aeromagnetic surveys. Extrusive volcanic rocks related to these intrusives are found in the north shore volcanics, widespread volcanic assemblages in the western part of the Upper Peninsula of Michigan and some flows in northern Wisconsin. In Minnesota the intrusive rocks are known as the Duluth Complex. These rocks form a belt extending north from Duluth to Hoyt Lakes then running northeasterly, then east to Lake Superior, not far south of the Canadian border. They underlie an area of about 20,000 square miles with considerable outcrop, or covered by a thin layer of glacial deposits.

The rocks of the Duluth Complex form a patchwork of layered intrusions. Some of the minerals contain iron and are quite dense, therefore they display distinct responses on gravity and magnetic surveys. Similar intrusive rocks in; Montana (the Stillwater Complex), Africa (the Bushveld Complex), Ontario (the Sudbury Igneous Complex), and Russia (the Noril'sk-Talnakh Intrusion) host economic deposits of copper-nickel, platinum group minerals, and some gold. Massive copper-nickel sulfide deposits with minor p.g.m. are commonly found near the base of the intrusive body, at or near the contact with intruded rocks or as dike like bodies intruded into the footwall rock. In addition platinum group minerals, and chromium horizons are found in reefs, commonly well above the intrusive contact.

In the mid 1960s outcrops and boulders of dark igneous rocks bearing sulfide copper-nickel minerals were recognized along the footwall contact of the Duluth Complex in the northeast trending section of the contact zone. Exploration of this area located mineral deposits which contained marginal economic mineralization estimated to be 4.4 billion tons with a copper content of 0.66% and a copper to nickel ratio of 3.3:1 (Listerud and Meineke).

Inferred geological maps of the footwall of the Duluth Complex based on geophysical interpretations, were prepared by Dr. Allan Spector and Associates under contract to the DNR. The maps display lithology, structure, depth to magnetic basement and mineral potential modeled from geophysical characteristics. The mineral potential areas are characterized by gravity and magnetic data (shown on profiles) which indicates the intrusives extend to the west of the mapped contact as sills, or features not explained by outcrop or drilling. Some of the northern MPAs correlate with geochemical anomalies mapped by Alminas (Alminas and Dahlberg).

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UPDATE ON THE GEOLOGICAL CORE AND SAMPLE REPOSITORY

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The Geological Survey Division (GSD) of the Michigan Department of Environmental Quality (DEQ) maintains the Geological Core and Sample Repository at Marquette, Michigan. The collection of drill core, cuttings, and other samples are from 63 counties in Michigan, including 14 of the 15 counties from the Upper Peninsula. The purpose of this collection is to act as a "rock" library and make the stored samples available to individual researchers and industry for geological study and to promote mineral and fuel exploration and development in Michigan.

As of January 1, 1996, there are 771 drill holes containing 251,000 feet of actual core, mostly from the Upper Peninsula. Another 365 holes have abbreviated core representing 124,000 feet. Also, an additional 202 holes have cuttings that represent 54,000 feet. In addition to the exploration drill holes, the repository is storing oil and gas cores and cuttings from throughout the State. Since January, 1994, selected cuttings from all new oil and gas wells drilled in Michigan have been sent to the repository. The 317 wells have cuttings that represent over 538,000 feet. An additional 9,100 feet of oil and gas core is also in storage.

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

The GSD's metallic mine and data collection is also stored at the repository. This includes thousands of surface and underground maps from early to more recent mines from the western one-half of the Upper Peninsula. Reports and other miscellaneous information is also available from this same area. This collection helps in the understanding of the geology and mineral resource potential of the State, as well as being an aid to public safety and land use planning. It is a record of potential mine subsidence areas of the State which should be avoided when construction is planned.

The repository occupies two separate buildings. The first building is 4,000 square feet with electricity and a heated examination room. The second building contains 3,200 square feet of storage space and is adjacent to the main building. Retrieval, replacement, splitting, and slabbing of material is provided by staff. Limited sampling of material is allowed and borrowing cores and other samples is possible on a case-by-case basis. Currently, there are no user fees. The facility is open by appointment, Monday through Friday, 8:00 a.m. to 4:30 p.m. Also, a complete inventory of the Core and Sample Repository is available. For an appointment or more information, call Bill Swenor, Geological Technician, at the Upper Peninsula Field Headquarters in Marquette at 906- 228-6561.

The GSD also maintains oil and gas well cuttings from over 10,000 wells drilled prior to 1994 and over 45,000 drillers logs and thousands of geophysical logs. Contact the Petroleum Geology and Production Unit in Lansing for more information at 517-334-6930. For Statewide water well logs and microfilm records, contact Lisa Farhat in the Administrative Support Unit at 517-334-6936. Copies of all Upper Peninsula water well records and well cuttings from over 600 selected wells are stored at the DNR Escanaba Office. Call Frank Chenier at 906-786-2351 for more information.

OUTCROP AND SUBSURFACE CORE ANALYSIS AND RELATIONSHIP TO REGIONAL HYDROCARBON PROSPECTIVENESS OF THE MIDDLE PROTEROZOIC NONESUCH FORMATION IN NORTHERN WISCONSIN AND MICHIGAN

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The Middle Proterozoic Nonesuch Formation, often described as a hydrocarbon generating source rock, partially composes the sedimentary rock infill sequence of the Midcontinent Rift System in northern Wisconsin and Michigan. The exploration potential of the Nonesuch Formation, acting as both a hydrocarbon source and reservoir unit, is supported by oil seeps in the White Pine Mine, White Pine, MI, and numerous geochemical studies that demonstrate that the oil in the White Pine Mine is derived from the Nonesuch Formation.

Outcrop, subsurface core samples, and an oil sample from the White Pine Mine were collected, along an approximate 150 mile transect from northwest WI northeast to the Keweenaw Peninsula of MI, and analyzed for their organic geochemical characteristics (Figure 1). In addition, the rate of kerogen decomposition was measured on a Nonesuch Formation shale core sample. The kinetic results suggests a high thermal exposure is required to convert Nonesuch Formation kerogen into hydrocarbons, and the Nonesuch Formation is a poor to fair source rock in the areas examined and presumably never was a high quality hydrocarbon source rock.

While we do not discount the possibility of Midcontinent Rift hydrocarbon accumulations in the study area, successful hydrocarbon exploration, targeting the Nonesuch Formation in the northern Midcontinent Rift for major reserves (over 10 million barrels of oil equivalent) is unlikely.

Outside the Nonesuch Formation outcrop area, the hydrocarbon prospectiveness is less well known. However, with release of the former proprietary Amoco St. Amour #1-29R core (Alger County, MI), the known deposition of Nonesuch-type stratigraphy is extended eastward to the longitude of Munising. Here 182 ft of brown, gray, and black fine-grained clastics, enveloped in 46 and 50 ft basalt flows, underlie typical Copper Harbor Conglomerate rocks. This diversion from the Oronto Group type-section sequence suggests an earlier initiation of Nonesuch-style deposition in the eastern Lake Superior Basin. Consideration of multiple time periods of Nonesuch-type deposition during the extension phase of Midcontinent Rift development would indicate the hydrocarbon potential of the Middle Proterozoic of the midcontinent U. S. is yet to be fully evaluated.

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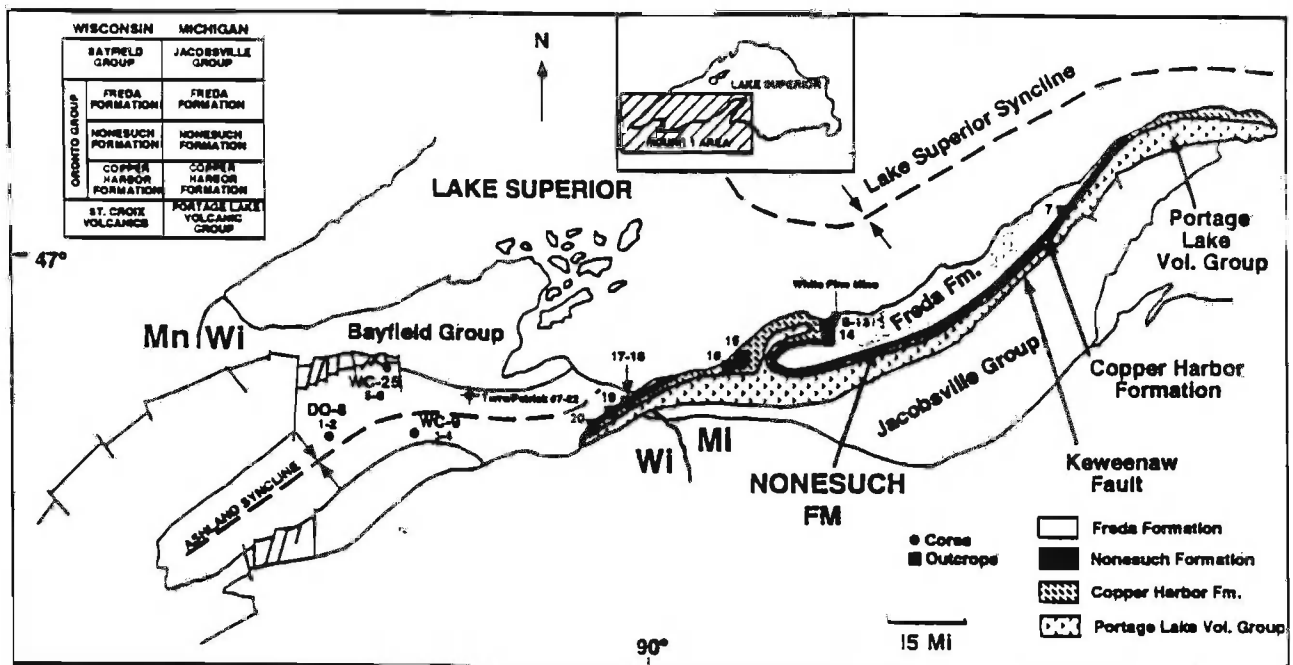


Figure 1. Geologic and location map of the southern Lake Superior region. Circles identify cored sites (1-6) of the Nonesuch Formation by the Bear Creek Mining Company. Squares identify outcrop sections (7-20) where Nonesuch Formation samples were collected. Map redrawn from Elmore and others, 1989, and Allen and others, in press.

A New Bathymetric Map of Lake Superior

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INTRODUCTION

The Large Lakes Observatory is producing a new bathymetric map of Lake Superior using data collected by the National Ocean Survey (formerly the U.S. Coast and Geodetic Survey) and archived at the National Geophysical Data Center in Boulder, Colorado. This data is supplemented with data digitized from earlier bathymetric charts to create maps that show detail never before attained.

The initial phase of this project is focused on western third of Lake Superior, from Duluth up to the international border near Isle Royale. Subsequent phases of this project will address the central and eastern portions of the lake.

DATA ANALYSIS

After the data are received they are carefully checked to identify and remove bad data points. Maps are created using the GMT software system (Wessel and Smith, 1991) for gridding and contouring. The data are fit to a 3-minute grid. Figure 1 shows an example of the maps produced. This example shows the bathymetry of the lake at its westernmost extent near Duluth, Minnesota. The map is contoured at 5 m intervals.

The new map reveals details not previously seen in earlier bathymetric maps of the lake. The steep slope of the North Shore of Minnesota exhibits irregular ridges and channels that probably correlate with dikes and fracturing of the basalt exposed on the shoreline. Besides contour maps, the GMT package can also produce a variety of other displays of the data. Figure 2 illustrates an example of the shaded relief maps that GMT can produce. This type of display can enhance low relief structures which are not readily observed in the contour displays. In this particular example, the lake floor near the Wisconsin south shore is shown illuminated by a light source located at 120 degrees to the lake. The lake floor exhibits a well developed network of low amplitude ridges and furrows that trend approximately NE-SW. These features are probably related to the glacial history of the Lake Superior region.

CONCLUSION

The GMT software system is being used to create a new bathymetric map for Lake Superior. The new map reveals details not previously seen in earlier maps of the lake. Subtle features on the lake floor can be enhanced using the tools available in GMT.

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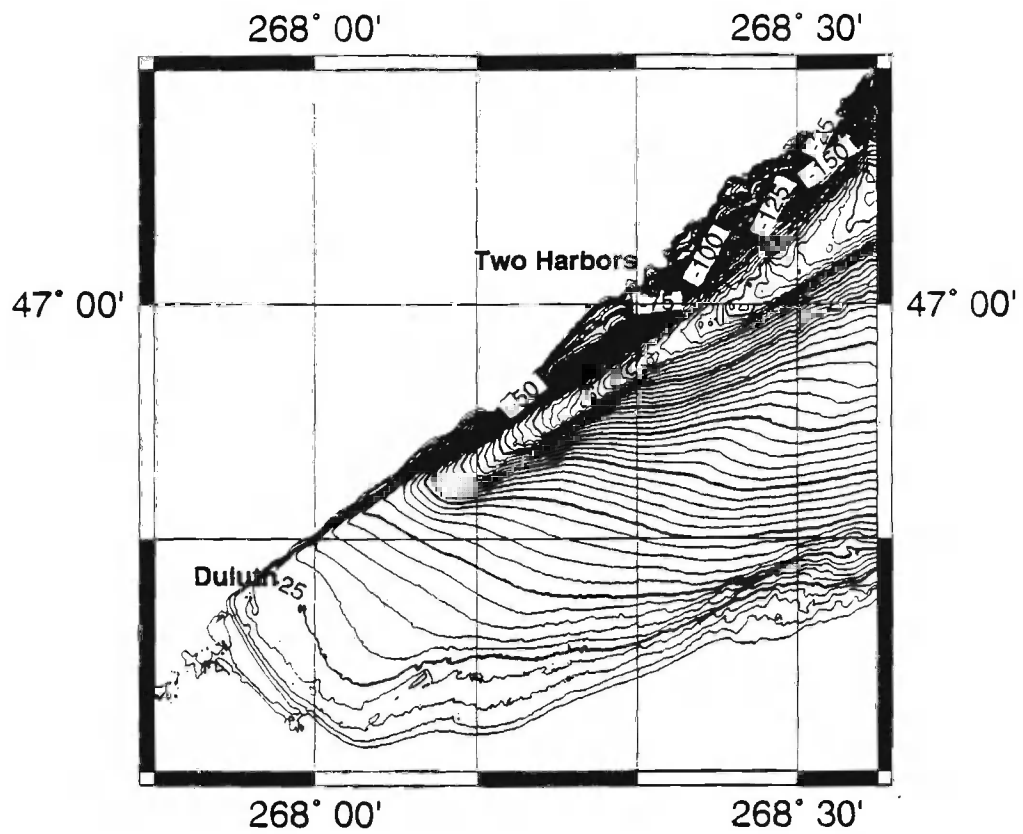


Figure 1. Bathymetric map of western Lake Superior between Duluth and Two Harbors. (5m contours)

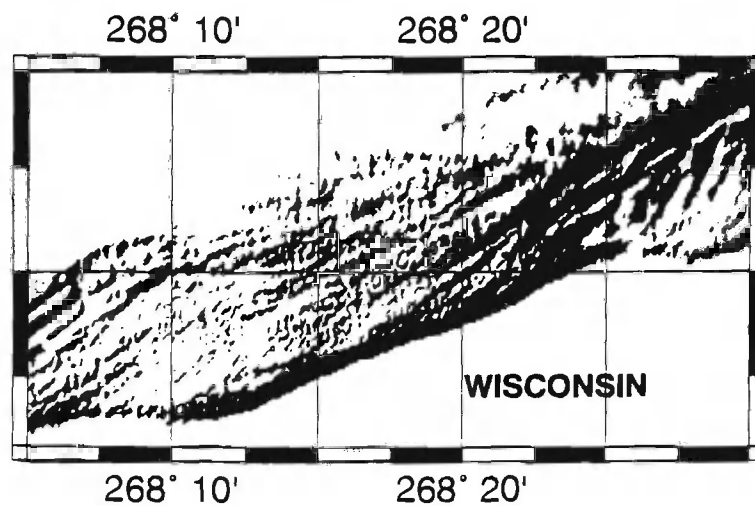


Figure 2. Shaded relief map of the lake floor near the Wisconsin south shore. Source of illumination located 120 degrees from the map.

REGIONAL FINITE STRAIN PATTERNS IN PROTEROZOIC SLATES AND
QUARTZITES: IMPLICATIONS FOR HETEROGENEOUS STRAIN RELATED
TO FLEXURAL SLIP FOLDING IN THE MARQUETTE SYNCLINORIUM

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Proterozoic rocks in the Marquette synclinorium are part of a sequence of deformed metasediments that extends from northern Michigan (Marquette Range Supergroup; MRSG) to Minnesota (Animikie Group). Slates in the MRSG near Marquette, Michigan, contain reduction spots, sandstone dikes, and deformed veins. Quartzites contain conglomerates, ellipsoidal spots, deformed veins, deformed rutile needles, and grain aggregates. These strain indicators are present in rocks that experienced weak to substantial distortions, and they were used to characterize regional finite strain patterns.

Quartzites in open folds show no indication of being strained. Strains in quartzites can be discerned where fold limbs dip greater than 60 degrees, and the largest strain ratios were observed in steep and overturned limbs. Strains in quartzite are heterogeneous, and the deformation style ranges from slight constriction to slight flattening; strain ratios are less than 1.3.

Argillites experienced early compactional strain and slight distortions related to the development of open flexures. Strains must have developed in early stages of folding, because veins are buckled or stretched even in weakly deformed argillites. Strains are heterogeneous, particularly along contacts between units that have large ductility contrasts. Angular shear strain estimates indicate extensions locally exceed 200 percent. These strains are localized in slate beds, and are not representative for the MRSG at the regional scale.

Strain ratios for slates are approximately twice those observed for quartzites in closed and overturned folds. The orientation of the principal strain axes in fold limbs show a consistent relation to fold geometry (except near major shear zones); the XY plane is approximately parallel to the axial trend of the Marquette trough, and X (maximum stretch) is subvertical.

Major structural features in the MRSG appear to have been inherited from the Archean basement. Fold geometry is consistent with basement-controlled tectonics involving translations along faults and shear zones in the Archean blocks. Regional strain patterns and orientations of penetrative fabric support a heterogeneous strain model that includes folding related to flexural slip.

A STRUCTURAL AND KINEMATIC ANALYSIS OF THE McCASLIN FORMATION NEAR McCASLIN MOUNTAIN, WISCONSIN

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ABSTRACT

Located along the north edge of the Wolf River batholith in northeastern Wisconsin is the McCaslin Formation. The formation is one of several Precambrian quartzite bodies that lie within the Penokean orogen and may be Penokean in age (LaBerge, Klasner and Myers, 1991). As the dominant foci of Mancuso (1960) and Olson (1982) were the the lithology and provenance of the McCaslin, our field study addressed its structure and kinematics. Detailed structural mapping was carried on within a four-section area of the McCaslin near McCaslin Mountain. Kinematic analysis involved the identification of sense-of-movement indicators in the field and the laboratory, as well as Fry (1979) analysis.

Our studies showed the following:

- 1) The McCaslin is mostly a thick-bedded orthoquartzite with a conglomeratic unit at its base.
- 2) Foliation is generally weak or absent except along two newly discovered zones of intense shearing.
- 3) Great-circle pi plots to bedding indicate the area is folded gently toward the northeast.
- 4) Within the study area the quartzite is exposed as two limbs which diverge toward the northeast; the southern limb is stratigraphically overturned toward the south.
- 5) Fry analyses of the quartzite and c-s fabrics within the shear zone indicate thrusting toward the south in the main shear zone.

Based on these findings we conclude that, in the area of study, the McCaslin Formation is part of a south-verging fold-thrust belt. We also suggest that the McCaslin is a part of the family of quartzite bodies that include the Baraboo and Waterloo, which were thrust southward during convergent Penokean tectonism. This suggests that the McCaslin is pre-Penokean and significantly older than previous interpretations.

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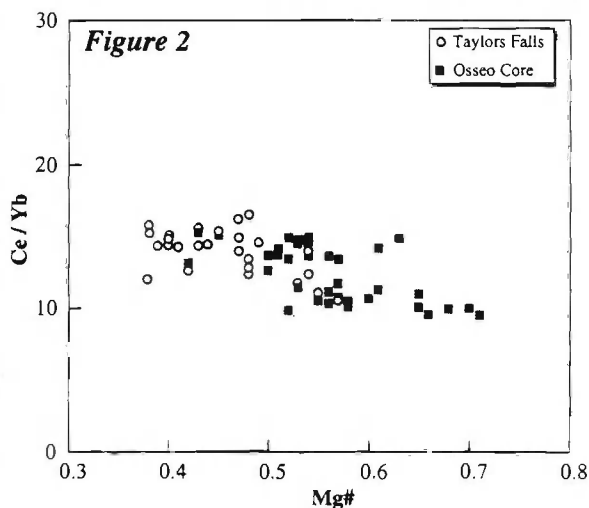
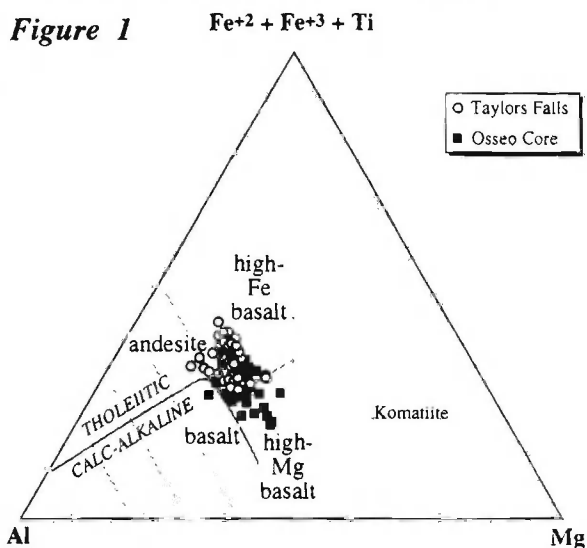
Geochemistry of Chengwatana Volcanic Group Near Taylors Falls and From Osseo Core

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Previous studies of the composition and character of volcanism in the Keweenaw (1100 Ma) Midcontinent Rift have primarily focused on the well-exposed flow sequences in the Lake Superior region. This study presents geochemical data of flows from the more poorly exposed Chengwatana Volcanic Group of the Taylors Falls region and sampled by drill core (Osseo, Minnesota).

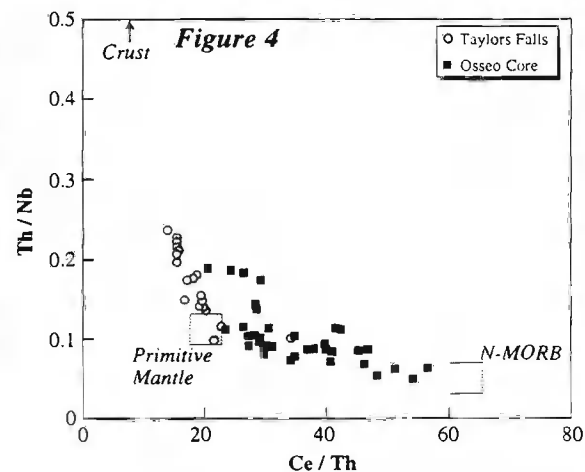
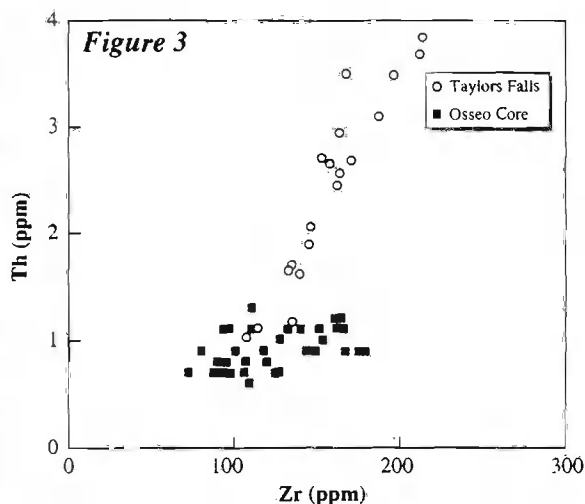
A 3000 meter thick section of the Chengwatana volcanic Group is exposed in the Taylors Falls - St. Croix Falls region. This section is composed primarily of mafic volcanic flows with minor interflow sedimentary rock. The basalt flows are high-Fe tholeiites (Figure 1) with plagioclase phenocrysts and ophitic to sub-ophitic clinopyroxene. Much of the basalt is olivine-normative or weakly quartz-normative, but olivine is not present in thin section. Abundant secondary chlorite, epidote, and actinolite indicate that the group was metamorphosed to greenschist facies. These basalts are characterized by low Mg#s (0.58-0.37) and Ni contents (185-36 ppm) which indicate that the flows have undergone significant fractionation. Flows near the top of the

exposed section have lower Mg#, Ni, Cr, and higher TiO_2 and P_2O_5 and indicate that the younger flows are the most fractionated. Incompatible element abundances are inversely correlated with Mg#; samples on most variation plots can be grouped into high- and low trace element groups (e.g. Ti, P, Zr). The basalts are enriched in the light rare earth elements and Th (Figures 2 & 3), but are variably depleted in Ta and Nb relative to Ce and Th (Figure 4). Initial $^{143}\text{Nd}/^{144}\text{Nd}$ compositions (1100 Ma) of the group range from 0.51122 to 0.51099 (initial $\epsilon_{\text{Nd}} = +0.1$ to -4.5), but ten of twelve samples have Nd isotopic compositions that fall within a narrow range (initial $\epsilon_{\text{Nd}} = -1.6$ to -2.5); flows with the highest ($+0.1$) and lowest (-4.5) initial ϵ_{Nd} values have isotopic compositions that are inversely correlated with trace element abundances and ratios (e.g. La/Yb, Th/La, Th/Ta). The combined major and trace element and Nd isotopic data suggest that the flows at Taylors Falls originated by variable frac-



tional crystallization and crustal contamination of asthenospheric melts that interacted with enriched lithospheric mantle.

More than 900 meters of mafic volcanic flows were sampled by a drill core near Osseo. Petrographic features and major element compositions of these flows are similar to the flows from the Taylors Falls region except they are generally more primitive ($\text{SiO}_2 = 44\text{-}50$ wt. %; $\text{Mg\#} = 0.72\text{-}0.42$; $\text{Ni} = 200\text{-}70$ ppm). Most of the Osseo flows would be grouped with the low- TiO_2 flows near Taylors Falls, however some Osseo flows have very high P_2O_5 (>0.39 wt. %). Several fractionation cycles can be recognized in the sequence and there is an overall trend toward more evolved flows in the upper part of the Osseo core similar to the trend seen in the Chengwatana section exposed near Taylors Falls. Analyses of Osseo and Taylors Falls flows plot in identical regions on diagrams of Nb/Y versus Zr/TiO_2 and Ti-Zr-Y and are most similar to transitional basalts and continental tholeiites. Osseo flows exhibit lower trace element abundances (e.g. REE, Zr, Y) and ratios (e.g. Ce/Yb , Th/La) consistent with their more primitive major element compositions (Figures 2,3 & 4). On diagrams involving elements that are sensitive indicators of crustal and mantle components (e.g. $\text{Mg\#}$ versus Nb/Nb^* , Th-Nb/16-Hf/3 ; Ce/Th versus Th/Nb) Osseo flows are displaced toward more mantle compositions relative to the Taylors Falls flows (Figures 3 & 4). These features indicate that the melts sampled in the Osseo core underwent less interaction with continental crust or subcontinental lithosphere than those near Taylors Falls. If the Osseo flows are stratigraphically higher, as suggested by their generally lower pressure metamorphic mineral compositions (Naiman et al., this volume), then the Chengwatana flows might record a decrease in a 'crustal' component as magmatism progressed. Furthermore, the Chengwatana flows of the Osseo core appear to contain a greater 'depleted mantle' component (Figure 4). Similar trends have been recognized in other Keweenaw basaltic flow sequences in the Lake Superior region (Shirey et al., 1994; Nicholson et al., 1995). This may suggest that magmas in the later stages of rifting were produced by melting a greater proportion of depleted asthenosphere and that these melts underwent less contamination during their passage through the lithosphere.



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