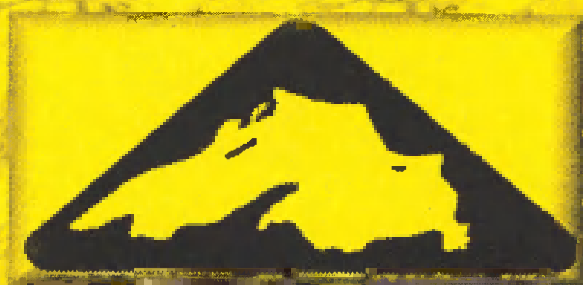


**FORTY-SIXTH ANNUAL MEETING
INSTITUTE ON LAKE SUPERIOR
GEOLOGY**

Thunder Bay, Ontario May 08-13, 2000



PROCEEDINGS VOLUME 46

**PART 1: PROGRAM AND
ABSTRACTS**

46th I.L.S.G.

Program
& Abstracts

May 8-13, 2000



*Hosted at Lakehead University
by the Geology Department
Thunder Bay, Ontario Canada*



46th Annual Meeting

INSTITUTE ON LAKE SUPERIOR GEOLOGY

Volume 46 contains the following parts:

Part 1: Program and Abstracts

Part 2: Field Trip Guidebook

- 1 — Geology of the Mesoproterozoic Sibley Group
- 2 — Geology of the Lac des Iles PGE-Cu-Ni Mine
- 3 — Geoarcheology and deglaciation history of the Thunder Bay area
- 4 — Geology of the Paleoproterozoic Gunflint Formation
- 5 — Glacial history and regional till sampling in the Archean Shebandowan Greenstone Belt
- 6 — Geology of the Archean Steep Rock Lake - Finlayson Lake Greenstone Belt

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

Argast, A., 2000. Chemistry and mineralogy of Lower Chocoma Group rocks, Dickinson County, Michigan, [abstract]: Institute on Lake Superior Geology Proceedings, 46th Annual Meeting, Thunder Bay, ON, 2000; v.46, Part 1, p. 1-2.

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INSTITUTE ON LAKE SUPERIOR GEOLOGY

CONTENTS

Proceedings Volume 46

Part 1—Program and Abstracts

Editor: Stephen A. Kissin

Institutes on Lake Superior Geology, 1955-2000	i
Constitution of the Institute on Lake Superior Geology	iii
By-Laws of the Institute on Lake Superior Geology	v
Goldich Medal Guidelines	vi
Past Goldich Medallists	viii
Goldich Medal Committee	viii
Citation for 2000 Goldich Medal Recipient	ix
Student Travel Awards	xi
Student Travel Award Application Form	xii
Student Paper Awards	xiii
Student Paper Awards Committee	xiii
Board of Directors	xiv
Local Committees	xiv
Banquet Speaker	xv
Report of the Chair of the 45th Annual Institute Meeting	xvi
Program	xix
Abstracts	1

INSTITUTES ON LAKE SUPERIOR GEOLOGY, 1955-2000

#	DATE	PLACE	CHAIRS
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 (note correction)
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. Myers
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. Myers
38	1992	Hurley, Wisconsin	A.B. Dickas

39	1993	Eveleth, Minnesota	D.L. Southwick
40	1994	Houghton, Michigan	T.J. Bornhorst
41	1995	Marathon, Ontario	M.C. Smyk
42	1996	Cable, Wisconsin	L.G. Woodruff
43	1997	Sudbury, Ontario	R.P. Sage, W. Meyer
44	1998	Minneapolis, Minnesota	J.D. Miller, M.A. Jirsa
45	1999	Marquette, Michigan	T.J. Bornhorst, R.S. Regis
46	2000	Thunder Bay, Ontario	S.A. Kissin, P. Fralick

CONSTITUTION

OF THE INSTITUTE ON LAKE SUPERIOR GEOLOGY

(Last amended by the Board—May 8, 1997)

- 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 persons who have registered for an annual meeting within the past three years, and those who indicate interest in being a member according to guidelines approved by the Board of Directors.
- Article V Meetings
The organization shall meet once a year. 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 Chair, Secretary-Treasurer, and the last three past Chairs; 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 Chair so as to bring the membership of the board to five members.

Article VII Officers

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

A. The Chair shall be elected each year by the Board of Directors, who shall give due consideration to the wishes of any group that may be promoting the next annual meeting. His/her term of office as Chair will terminate at the close of the annual meeting over which he/she presides, or when his/her successor shall have been appointed. He/she will then serve for a period of three years as a member of the Board of Directors.

B. The Secretary-Treasurer shall be elected at the annual meeting. His/her term of office shall be four years, or until his/her successor shall have been appointed.

Article VIII Amendments

This constitution may be amended by a majority vote (majority of those voting) of the membership of the organization.

BY-LAWS OF THE INSTITUTE ON LAKE SUPERIOR GEOLOGY

I. Duties of the Officers and Directors

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

II. Duties and Expenses

- A. Regular membership dues of \$5.00 or less on an annual basis shall be assessed each member as determined by the Board of Directors..
- B. Registration fees for the annual meetings shall be determined by the Chair in consultation with the Board of Directors. The registration fees can include expenses to cover operations outside of the annual meeting as determined by the Board of Directors. It is strongly recommended that registration fees be kept at a minimum to encourage attendance of 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 (majority of those voting) of the membership of the organization; provided that such modifications shall not conflict with the constitution as presently adopted or subsequently amended.

GOLDICH MEDAL GUIDELINES

(Adopted by the Board of Directors, 1981; amended 1999)

Preamble

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

The first award was made by ILSG to Sam Goldich in 1979 for his many contributions to the geology of the region extending over about 50 years. Subsequent medalists and this year's recipient are listed in the table below.

Award Guidelines

- 1) The medal shall be awarded annually by the ILSG Board of Directors to a geologist whose name is associated with a substantial interest in, and contribution to, the geology of the Lake Superior region.
- 2) The Board of Directors shall appoint the Goldich Medal Committee. The initial appointment will be of three members, one to serve for three years, one for two years, and one for one year. The member with the briefest incumbency shall be chair of the Nominating Committee. After the first year, the Board of Directors shall appoint at each spring meeting one new member who will serve for three years. In his/her third year this member shall be the chair. The Committee membership should reflect the main fields of interest and geographic distribution of ILSG membership.
- 3) By the end of November, the Goldich Medal Committee shall make its recommendation to the Chair 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, inform the medallist, and 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.

Nominating Procedures

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

Selection Guidelines

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

GOLDICH MEDALISTS

1979	Samuel S. Goldich	1990	Kenneth C. Card
1980	<i>not awarded</i>	1991	William Hinze
1981	Carl E. Dutton, Jr.	1992	William F. Cannon
1982	Ralph W. Marsden	1993	Donald W. Davis
1983	Burton Boyum	1994	Cedric Iverson
1984	Richard W. Ojakangas	1995	Gene LaBerge
1985	Paul K. Sims	1996	David L. Southwick
1986	G.B. Morey	1997	Ronald P. Sage
1987	Henry H. Halls	1998	Zell Peterman
1988	Walter S. White	1999	Tsu-Ming Han
1989	Jorma Kalliokoski	2000	<i>John C. Green</i>

GOLDICH MEDAL COMMITTEE 1999-2000

(Committee membership extends through the meeting year shown; replacement members will be selected during the Board of Directors' annual meeting of that year. Note that the term of each committee member was extended 1 year by the 1999 Board of Directors)

John Klasner (2000)

Western Illinois University, Macomb, Illinois

Mark Smyk (2001)

Ontario Geological Survey, Thunder Bay

Rod Johnson (2002)

Rod Johnson and Associates, Negaunee, Michigan

CITATION

John C. Green, **2000 Goldich Medal Recipient**

John C. Green, Professor Emeritus of the Department of Geological Sciences, University of Minnesota-Duluth, has had a long, distinguished, and on-going career in the Lake Superior region.

He received his B.A. Degree in Geology from Dartmouth College in 1953. He then spent a year amid Norskies at the University of Oslo on a Fulbright Fellowship. He received his M.A. in 1956 and his Ph.D. in 1960, both from Harvard University. With his dissertation on Appalachian geology of an area in New Hampshire/Maine not quite finished, New Englanders John and Jan moved to Duluth in 1958 when John accepted the position at UMD. Most of his subsequent summers were spent mapping in northern Minnesota for the Minnesota Geological Survey. He did the Archean portion of the Gabbro Lake 15' Quadrangle (Green, Phinney, and Weiblen, 1966), the first detailed map in the remapping of the Precambrian that was undertaken by the MGS under the leadership of Paul Sims. Whereas Minnesota has been his primary working domain, he has taught at the Wasatch-Uinta Geology Field Camp in Utah for six summers, has spent a year as a NASA-NRC Senior Research Associate at the Johnson Space Center in Houston, and has traveled widely – including Japan, Iceland, and Namibia – to study volcanic rocks.

John has served as Head of UMD's Department of Geology, has served on dozens of university committees, and has chaired several of them. He was on the All-University Council on Environmental Quality for eight years. He has chaired the Board of Directors of the Lake Superior Basin Studies Center. He has taught 20 different courses, including several that deal with environmental geology, one of his many interests. He has supervised 13 M.S. theses and has served on 61 M.S. and 5 Ph.D. examining committees. He has authored or co-authored more than 100 publications, maps, field guides, and abstracts.

John's main scientific interest has been the North Shore Volcanic Group – stratigraphy, physical volcanology, structure, petrology, and chemistry – and the Midcontinent Rift System in general. Indeed, the name of John C. Green is synonymous with the NSVG.

He is a most careful and observant field geologist. Today, at the age of 68, long after many geologists would have hung up their field boots and settled for writing the umpteenth summary paper about their glory days, he is still out their leading field trips, beating the bush and the bugs, and hunting for the outcrops that will bring him a little closer to the truth. John doesn't just look at the rocks! He is the rare "complete naturalist", for he knows every species of flora and fauna as well. And, he is very active in preservation of nature for the enjoyment of all. His foresight, initiative, and drive resulted in the preservation of Sugarloaf Cove/Point near Schroeder on the North Shore, with its unique geology, flora, and cultural history, as a protected Natural and Scientific

Site. He was instrumental in the founding and continuance of SICA, the Sugarloaf Interpretative Center Association.

One of his more recent accomplishments is his book on the geology and natural history of the state parks of the North Shore, entitled "Geology on Display". It was published by the Minnesota DNR in 1996.

John has been one of the strongest supporters of the Institute on Lake Superior Geology over the last several decades. He presented his first talk there in 1959, and has added 28 abstracts since then. It is because of the dedication and support of people like John, that the ILSG has remained such a viable and healthy organization for nearly half a century.

John C. Green - the tireless field geologist, the laboratory scientist, the demanding teacher, the knowledgeable and cooperative colleague, the educator of the public, the complete naturalist, and the advocate of ILSG - is most deserving of the Goldich Medal! All of us assembled here, as well as wife Jan, daughters Martha and Sarah, sons-in-law Joe and Richard, and five grandchildren, are proud of you!

Congratulations, J.C.!

EISENBREY STUDENT TRAVEL AWARDS

The 1986 Board of Directors established the ILSG Student Travel Awards to support student participation at the annual meeting of the Institute. The name "Eisenbrey" was added to the award in 1998 to honor Edward H. Eisenbrey (1926-1985) and utilize contributions made to the 1996 Institute meeting in his name. "Ned" is credited with discovery of significant volcanogenic massive sulfide deposits in Wisconsin, but his scope was much broader—he has been described as having unique talents as an ore finder, geologist, and teacher. These awards are intended to help defray some of the direct travel costs of attending Institute meetings, and include a waiver of registration fees, but exclude expenses for meals, lodging, and field trip registration. The number of awards and value are determined by the annual Chair in consultation with the Secretary-Treasurer. Recipients will be announced at the annual banquet.

The following general criteria will be considered by the annual Chair, 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 from the meeting location.
- 5) Each travel award request shall be made in writing to the annual Chair, and should explain need, student and author status, and other significant details. The form below is optional.

Students can use the form below, or consult the Institute's web page (ilsgeology.org) to apply. Successful applicants should contact the meeting chair to receive their awards during the meeting.

INSTITUTE ON LAKE SUPERIOR GEOLOGY



Eisenbrey Student Travel Award Application

Student Name: _____ Date: _____

Address: _____

email: _____

Department Head-Typed

Educational Status: _____

Department Head-Signature

Are you the senior author of an oral or poster paper? YES _____ NO _____

Will any other students be traveling with you?

Who? _____

Statement of need (use additional page if necessary)

Please return to:

STUDENT PAPER AWARDS

Each year, the Institute selects the best of the student presentations and honors presenters with a monetary award. Funding for the award is generated from registrations of the annual meeting. The Student Paper Committee is appointed by the annual meeting Chair in such a manner as to represent a broad range of professional and geologic expertise. Criteria for best student paper—last modified by the Board in 1997—follow:

- 1) The contribution must be demonstrably the work of the student.
- 2) The student must present the contribution in-person.
- 3) The Student Paper Committee shall decide how many awards to grant, and whether or not to give separate awards for poster vs. oral presentations.
- 4) In cases of multiple student authors, the award will be made to the senior author, or the award will be shared equally by all authors of the contribution.
- 5) The total amount of the awards is left to the discretion of the meeting Chair and Secretary-Treasurer, but typically is about \$300 US.
- 6) The Secretary-Treasurer maintains, and will supply to the Committee, a form for the numerical ranking of presentations. This form was created and modified by Student Paper Committees over several years in an effort to reduce the difficulties that may arise from selection by raters of diverse background. The use of the form is not required, but is left to the discretion of the Committee.
- 7) The names of award recipients shall be included as part of the annual Chair's report that appears in the next volume of the Institute.

Student papers will be noted (*) on the Program.

2000 STUDENT PAPER AWARDS COMMITTEE

Manfred M. Kehlenbeck, Chair

Lakehead University, Thunder Bay, Ontario

Terrence J. Boerboom

Minnesota Geological Survey, St. Paul, Minnesota

Graham C. Wilson

Turnstone Geological Ltd., Campbellford, Ontario

2000 BOARD OF DIRECTORS

(Board membership extends through the meeting year shown in parentheses)

Stephen A. Kissin, Chair (2003)

Lakehead University, Thunder Bay, Ontario

Theodore J. Bornhorst (2002)

Michigan Technological University, Houghton, Michigan

James D. Miller (2001)

Minnesota Geological Survey, St. Paul, Minnesota

Ronald P. Sage (2000)

Ontario Geological Survey

Mark Jirsa (2000) Institute Secretary-Treasurer

Minnesota Geological Survey, St. Paul, Minnesota

LOCAL COMMITTEES 2000

GENERAL CO-CHAIRS: Stephen A. Kissin and Philip W. Fralick

PROGRAM AND ABSTRACTS EDITORS: Stephen A. Kissin

FIELD TRIP COORDINATOR AND GUIDEBOOK EDITOR: Philip W. Fralick
Assistance to the local committee was provided by the following individuals:

Karen Farrier - Lakehead University

Manuscript preparation, accounting and communications

Sam Spivak - Lakehead University

Graphics

Becky Rogala - Lakehead University

Manuscript preparation and audio-visual

Mark Smyk - Ministry of Northern Development and Mines
Organization

SESSION CHAIRS (in order of appearance):

Wed. AM

Manfred Kehlenbeck

Lakehead University — Thunder Bay

Dick Ojakangas

University of Minnesota — Duluth

Wed. PM

Ted Bornhorst

Michigan Technological University — Houghton

Mike Mudrey

Wisconsin Geological and Natural History Survey — Madison

Thurs. AM

Andrew Mitchell

DST Consulting Engineers — Thunder Bay

Tony Naldrett

Consultant — Toronto

Thurs. PM

Mark Smyk

Ontario Geological Survey — Thunder Bay

Jim Miller

Minnesota Geological Survey — Duluth

BANQUET SPEAKER 2000

Bruce Simonson

Oberlin College

"Depositional settings and Early Diagenesis of Large Precambrian Iron Formations"

**REPORT OF THE 45th ANNUAL MEETING OF THE
INSTITUTE ON LAKE SUPERIOR GEOLOGY**

Marquette, Michigan

**REPORT ON THE 45TH ANNUAL MEETING OF THE INSTITUTE
ON LAKE SUPERIOR GEOLOGY, MARQUETTE, MICHIGAN**

The 45th Annual Meeting of the Institute on Lake Superior Geology was held in Marquette, Michigan May 4-8, 1999 at the Ramada Inn. The meeting was co-sponsored by Northern Michigan University and Michigan Technological University. Robert S. Regis and Theodore J. Bornhorst co-chaired the annual meeting. The meeting was well attended with 120 geoscientists registering from 10 different states, three Canadian provinces, and Switzerland. The meeting consisted of two pre-technical session and two post-technical session field trips, two days of technical sessions, and an evening banquet.

The Proceedings Volume 45 was published in two parts. Part 1- Program and Abstracts was edited by Robert S. Regis and Theodore J. Bornhorst. There were 33 published abstracts for the 22 oral and 11 poster presentations given in the technical sessions. Part 2 - Field Trip Guidebook, was edited by Theodore J. Bornhorst. There were 4 field trips and for two of them there were separate papers with supplementary information. The guidebook contained several colored maps and cross-sections.

Field trips continue to be an important component of the annual meeting of ILSG evidenced by 76% of attendees participating in 1 or more field trips. The guidebook contains 4 field trips:

Field trip 1 was titled "Early Proterozoic strata of the Marquette iron range, Michigan" and was lead by W.F. Cannon. This one-day field trip had 30 participants who visited classic geologic localities in the Marquette area.

Field trip 2 was titled "Archean Ishpeming greenstone belt and gold mineralization, Michigan" and was lead by T.O. Quigley, R.A. Mahin, D.J. Duskin, R.C. Johnson, T.J. Bornhorst, and G.W. Scott. This two-day field trip had 28 participants and visited localities focused on lithology, structure, and gold mineralization. New data on several gold prospects were presented.

Field trip 3 was titled "Tilden and Empire Mines of the Marquette iron range, Michigan" and was lead by G.W. Scott, P.M. Nordstrom, and H.M. Lukey. This one-day trip was very well attended with 45 participants. We thank the Tilden Mining Company and the Empire Iron Mining Partnership for allowing access to these two iron mines. Participants of this one-day field trip visited localities within the open-pit mines. This was the first time ILSG has visited either of these two mines. The last time a Michigan iron mine was visited by an ILSG field trip was 27 years ago in 1972.

Field trip 4 was titled "Paleozoic and glacial strata from Au Train to Grand Marais, Michigan" and was lead by R.S. Regis and J. Anderton. This one-day field trip had 16 participants. This is the first time ILSG has had a field trip in the Munising area and participants were able to see and learn about the geology of the Pictured Rocks National Lakeshore.

The banquet was attended by 99 out of the 120 participants at the annual meeting. Nelson Ham of St. Norbert College gave an excellent talk on glacial processes along the southern edge of the Laurentide ice sheet. A highlight of the banquet was the awarding of the 1999 Goldich medal to Tsu-Ming Han for his contributions to the North American iron ore industry. It is interesting to note that Tsu-Ming delivered a paper at the first ILSG annual meeting in 1955 and another at this meeting some 45 years later.

The technical sessions included two invited papers: "Cross Margin Transport in Lake Superior" presented by Sarah Green and "A New Approach to Historical Reconstruction: Combining Descriptive and Experimental Paleolimnology" presented by Charlie Kerfoot. We are grateful to the solicited presentations made by industry personnel associated with Cliffs Mining Services, Tilden Mining Company and Empire Iron Mining Partnership. Two students were selected for outstanding presentations. Ulrich Puschner (Basel, Switzerland) was awarded \$150 for his poster paper on metamorphism of the Portage Lake Volcanics in Michigan and Joy Loughry (Univ. Minnesota-Morris) was awarded \$150 for her oral presentation on the Crowduck Lake Group, Kenora, Ontario. Three students, David Ams (Kent State Univ., Ohio), Dyana Czeck (Univ. Minnesota), and Ulrich Puschner were awarded Eisenbrey Student Travel Awards for a total of \$800. All of these students presented papers at the meeting.

The Institute's Board of Directors met on May 6, 1999 and the following is an overview of the meeting.

1. Accepted the Report of the Chairs for the 44th ILSG.
2. Accepted the 1998-99 ILSG financial report. There was discussion on methods to encourage student attendance through monetary and other means. A lower cost for students to attend field trips, just like meeting registration, was acceptable.
3. Discussed guidelines for the Goldich Award.
4. Maintained the composition of the Goldich Medal Committee for one year.
5. Discussed recasting of the Goldich Medal.
6. Discussed and approved 2000 meeting location in Thunder Bay with Kissin and Fralick as co-chairs.
7. Discussed the possibility of a 2001 meeting in Sault Ste Marie, Michigan.
8. Discussed defraying the meeting expenses for the secretary-treasurer. The Board approved waiving registration for all meeting events (registration, field trips, and banquet).
9. Approved a Corporate Resolution for the secretary-treasurer to conduct investments.
10. Reaffirmed Board commitment to the ILSG Newsletter and Web page. The Web page will be reorganized by Laurel Woodruff and Ted Bornhorst.
11. Agreed that only one of the two co-chairs would continue as primary board member. Ted Bornhorst will be the representative from the 1999 meeting.

We wish to thank all of the people who lead and prepared materials for the field trips and made presentations. While field trips continue as the traditional strength of ILSG, the presentations provide a forum for discussion of Lake Superior geology. Of course, there are many others who we acknowledge for contributing to the success of a meeting including the session chairs, best student paper award committee, ILSG Board members, and the staff of the Ramada Inn. We especially thank Suki Smaglik for all of her volunteer help with registration. Last we thank all of those who attended the 45th annual ILSG meeting, for without them there would not be an ILSG. Our "break even" budget model was based on indicated pre-meeting interest. As a result of

higher attendance than expected and some unexpected additional monies, the meeting generated a positive cash flow of a few thousands of dollars for ILSG.

We are personally satisfied with the overall outcome of the meeting and feel it was a success. While it is a lot of work to put on the ILSG annual meeting, it was well worth the effort. We encourage others to consider being chair or co-chairs of the ILSG annual meeting.

Ted Bornhorst and Bob Regis
Co-Chairs of the 45th Annual ILSG

CALENDAR OF EVENTS AND PROGRAM

MONDAY, MAY 8, 2000

0800-1800 **PRE-MEETING FIELD TRIPS**
All field trips leave and return each evening to Lakehead University

- 1) MESOPROTEROZOIC SIBLEY GROUP (*Day One*)
Leaders: Philip Fralick, Mark Smyk

TUESDAY, MAY 9, 2000

0800-1800 **PRE-MEETING FIELD TRIPS**

- 1) MESOPROTEROZOIC SIBLEY GROUP (*Day Two*)
Leaders: Philip Fralick, Mark Smyk
- 2) LAC DES ILES MINE (I)
Leader: Moe Lavigne
- 3) GEOARCHEOLOGY OF THE THUNDER BAY AREA
Leaders: Brian Phillips, Scott Hamilton, Joe Stewart, Pat Julig, Bill Ross

1700-2200 **REGISTRATION AT LAKEHEAD UNIVERSITY**
POSTER SESSION/CASH BAR MIXER
Agora/Faculty Lounge

WEDNESDAY, MAY 10, 2000

0800-1200 REGISTRATION/PRE-REGISTRATION PACKET PICK-UP

Session I: GEOLOGICAL OVERVIEW OF THE WESTERN SUPERIOR PROVINCE
University Centre Theatre

0900-0915 WELCOME AND OPENING REMARKS

0915-0945 **Kehlenbeck, M.M.**
A Review of Structures in Rocks of the Quetico Subprovince and Adjacent Terranes

0945-1015 **Davis, D.W.**
Western Superior Province: Geochronologic Aspects

1015-1040 COFFEE BREAK AND POSTER SESSION

1040-1110 **Tomlinson, K.**
Western Superior Province: Volcanological Aspects

1110-1140 **Fralick, P.W.**
Western Superior Province: Sedimentological Aspects

1140-1200 **Czeck, D.M.* and Hudleston, P.J.**
A Sequence of Folding and Dextral Transpression in the Seine River Conglomerates

1200-1310 LUNCH BREAK

1310-1330 **Davis, D.W., Amelin, Y., Nowell, G.M. and Parrish, R.R.**
Hf Isotope Study on Zircons from the Western Superior Province

1330-1350 **Pettigrew, N.T.*, Hattori, K.H. and Percival, J.A.**
Samuels Lake Intrusion: a PGE-bearing Quetico-type Intrusion in the Central, Western Quetico Subprovince, Northwestern Ontario

1350-1410 **Wilson, A.C.**
Archean Diamond Exploration Targets in the Michipicoten Greenstone Belt, Wawa, Ontario

1410-1430 **Morris, T.F., Sage, R.P. and Crabtree, D.C.**
Kimberlite, Base Metal, Gold and Carbonatite Exploration Targets, Derived from Overburden Heavy Mineral Data, Killala Lake Area, Northwestern Ontario

- 1430-1450 **Kärkkäinen, N. and Bornhorst, T.J.**
Small Mafic Intrusions of the Lake Superior Region: Targets for Titanium Exploration
- 1450-1510 COFFEE BREAK AND POSTER SESSION
- 1510-1530 **Bajc, A.F.**
Results of Regional Till Sampling in the Western Part of the Shebandowan Greenstone Belt, Northwestern Ontario
- 1530-1550 **Cannon, W.F. and Woodruff, L.G.**
Some Factors That Control the Distribution of Mercury in the Near-surface Environment of Isle Royale National Park, Michigan-earth, Wind and Fire
- 1550-1610 **Larson, P.C. and Mooers, H.D.**
Commination and Dilution of Glacial Indicators: Rate Estimates from Field Data
- 1610-1630 **Peterson, D.M.**
Geometry Between Gold-rich Subsidiary Shear Zones and Major Structures: Implications for Archean Lode-Gold Mineral Exploration
- 1630 ILSG Business Meeting
- 1800-1930 MIXER (*Residence Cafeteria*)
Cash Bar
- 1930-2130 ANNUAL BANQUET AND AWARDS PRESENTATION
Residence Cafeteria
- Announcement of 47th Annual Meeting location
 - Banquet Speaker: **Dr. Bruce Simonson**, Oberlin College

“Depositional Settings and Early Diagenesis of Large Precambrian Iron Formation”

THURSDAY, MAY 11, 2000

Session II: GEOLOGICAL OVERVIEW OF THE WESTERN SUPERIOR PROVINCE *University Centre Theatre*

- 0900-0930 **Lavigne, M.J.**
The Lac des Iles Mine, Northwestern Ontario
- 0930-1000 **Fralick, P.W.**
Western Superior Province: Proterozoic Sediments
- 1000-1030 **Kissin, S.A.**
Vein-type Deposits of the Thunder Bay Area
-
- 1030-1050 COFFEE BREAK AND POSTER SESSION
- 1050-1110 **Pueschner, U.* and Schmidt, S.T.**
Low-grade Metamorphic Zonation of the Keweenaw Portage Lake Volcanics on the Keweenaw Peninsula, Michigan
- 1110-1130 **Rampe, J.S.* and Holm, D.K.**
Modelling the Effect of Intermediate Temperature (350°-500°C) Mazatzal-Age Thermal Overprinting on Argon Diffusion from the Southern Lake Superior Region
- 1130-1150 **Hudak, G.J., Morton, R.L. and Dahlberg, H.**
Preliminary Volcanology and Hydrothermal Alteration Studies at the Five Mile Lake, Eagles Nest, and Quartz Hill Prospects: Implications for VMS-Style Mineralization in Northeastern Minnesota
- 1150-1300 LUNCH
- 1300-1320 **Green, J.C.**
Mystery Faults of the Cascade River, North Shore, or What Is this Granite Doing Here?
- 1320-1340 **Schulz, K.J. and Nicholson, S.W.**
Lithogeochemistry and Paleotectonic Setting of the Bend Massive Sulfide Deposit, Northern Wisconsin
- 1340-1400 **Van Schmus, W.R., MacNeill, L.C., Holm, D.K., Boerboom, T.J. and**

Jirsa, M.A.

The 1787-1772 Ma East-Central Minnesota Batholith: Precursor to Crustal Stabilization in the Lake Superior Region

- 1400-1420 **Schweitzer, D.J. *, Schnieder, D.A., Boerboom, T.J., Holm, D.K. and Van Schmus, W.R.**
Assessing the Extent of Early Proterozoic Penokean Versus ~1770-1760 Ma Metamorphism in East-Central Minnesota
- 1420-1440 **Holm, D.K., Hodges, K.V. and Hurtado, J.**
Results of $^{40}\text{Ar}/^{39}\text{Ar}$ Laser Microprobe Age Mapping of Muscovite from Precambrian Bedrock of the Southern Lake Superior Region
- 1440-1500 **Kissin, S.A., Okamoto, M., Addison, W.D. and Brumpton, R.G.**
A Possible Sudbury Ejecta Layer in the Gunflint Formation, Northwestern Ontario
- 1500-1520 COFFEE BREAK AND POSTER SESSION
- 1520-1530 STUDENT AWARDS
- 1530-1550 **North, J.**
Nature and Distribution of Logan Diabase Sills and Gabbro Channels in the Keweenawan Rift near Thunder Bay, Ontario: Brief Comparison to Noril'sk
- 1550-1610 **Medaris, L.G. Jr.**
The Barron Saprolite: Confirmation of Mature Chemical Weathering in the Source for Paleoproterozoic Quartz Arenites in the Lake Superior Region
- 1610-1630 **Argust, A.**
Chemistry and Mineralogy of Lower Chocelay Group Rocks, Dickinson County, Michigan
- 1630-1650 **Simonson, B.M.**
The Distinction Between Flat Pebble Conglomerates and Intraformational Breccias in Precambrian Iron Formations

POSTER PRESENTATIONS

Bandli, B.R.* and Saini-Eidukat, B.

Nomarski DIC Microscopy and Structural State Analysis of Plagioclases from the Duluth Complex, Minnesota

Beaster, K.F.*, Kohn, J.D.* and Havholm, K.G.

Wind or Water? Paleoenvironment of the Proterozoic Hinckley Sandstone, Northeastern Minnesota

Harris, E.C.A.* and Wirth, K.R.

Petrogenesis of granitic rocks of the Dunka River region, eastern Mesabi Range, Minnesota

Hauck, S.A., Bite, A. and Severson, M.

Copper Mineralization of Pyroxene Hornfelsed Archean Giants Range Batholith Footwall of the Keweenaw South Kawishwi Intrusion, Duluth Complex, NE Minnesota - Archean or Keweenaw Mineralization?

Jerde, E.A.

Magmatic Origins for Nathan's Layered Series: An Initial Reassessment of the Midcontinent Rift's First Major Plutonic Materials

Kean, W.F. and Luther, F.

Additional Paleomagnetic Studies of a Proterozoic Diabase Dike, in Pifher and Irwin Townships, Lake Nipigon District, Ontario

Kennedy, B.C.*, Wirth, K.R. and Vervoort, J.D.

Petrogenesis of the Midcontinent Rift Granophyric Complexes of Northern Minnesota

Luther, F.R.

Low-grade Metamorphism of an Archean Debris Flow, Irwin, Pifher and Meader Townships, Lake Nipigon Region, Ontario

Medaris, L.G. Jr. and Fournelle, J.H.

Tourmaline-bearing Quartz Veins in the Baraboo Quartzite: A New Occurrence of the Alkali-deficient Tourmaline, Foitite

Morris, T.F., Sage, R.P. and Crabtree, D.C.

Kimberlite, Base Metal, Gold and Carbonatite Exploration Targets, Derived from Heavy Mineral Data, Killala Lake Area, Northwestern Ontario

Peterson, D.M.

Geologic and GIS-based Lode-gold and Volcanogenic Massive Sulfide (VMS) Mineral

Potential Maps of a Portion of the Archean Vermillion Greenstone Belt, Northeastern Minnesota

Phillips, E.H.*, Wirth, K.R. and Morey, G.B.

Petrogenesis of the Enigmatic Aurora Sill, Mesabi Range, Minnesota

Sage, R.P.

The "Sandor" Diamond Occurrence, Michipicoten Greenstone Belt, Wawa, Ontario

Stott, G. and Berdusco, B.

Precambrian Features under the James Bay and Hudson Bay Lowlands

Vervoort, J.D., Wirth, K.R. and Kennedy, B.C.

Isotopic Constraints on the Origin of Granophyre Complexes in the Midcontinent Rift of Northeastern Minnesota

Wilson, A.

Archean Diamond Exploration Targets in the Michipicoten Greenstone Belt

Wolbers, J.A.* and Seifert, K.E.

Petrogenesis of the Silver Creek Dike: a 1.1 Ga Intrusion in the Midcontinent Rift

Woodruff, L.G., Attig, J.W. and Cannon, W.F.

Geochemical Impacts of an Undisturbed Mineral Deposit - Results from the Bend Deposit, Chequamegon National Forest, Wisconsin

FRIDAY, MAY 12, 2000

0800-1800

POST-MEETING FIELD TRIPS

All field trips leave and return each evening to Lakehead University, except for Field Trip 6, which will involve an overnight stay in Atikokan on May 12 (at the participant's expense).

4) PALEOPROTEROZOIC GUNFLINT FORMATION

Leaders: Pier Pufahl and Philip Fralick

5) QUATERNARY GEOLOGY, SHEBANDOWAN BELT

Leader: Andy Bajc

6) STEEP ROCK - FINLAYSON - LUMBY BELTS (Day One)

Leaders: Denver Stone, Kirsty Tomlinson, Ray Bernatchez and Philip Fralick

7) LAC DES ILES MINE (II)

Leader: Moe Lavigne

SATURDAY, MAY 13, 2000

0800-1800

FIELD TRIP 6 (Day Two)

Chemistry and Mineralogy of Lower Chocelay Group Rocks, Dickinson County, Michigan

ARGAST, Anne, Department of Geosciences, Indiana-Purdue University Fort Wayne,
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Rocks of the Chocelay Group rest on Archean basement in Dickinson County, Michigan. Most likely accumulated in the interval 1.9-2.1 Ga. ago, the Group consists of the basal, partly conglomeratic, Fern Creek Formation, overlain by Sturgeon River Quartzite and Randville Dolomite. Chocelay Group likely represents deposition in terrigenous and shallow marine environments with later units of the Marquette Range Supergroup (Menominee and Baraga Groups) transitioning upwards into deeper water, more active and isolated environments.

There are two alternate views for the origin of the Fern Creek Formation. Some interpret the Fern Creek (or its putative equivalents of Reany Creek and Enchantment Lake Formations farther north in Michigan) as examples of glaciogenic sediments, possibly synchronous with Gowganda glaciation (e.g., Pettijohn, 1943; Gair, 1981; Young, 1983; Ojakangas, 1984). Others interpret the Fern Creek as originating, for example, in fluvial, occasionally torrential environments (e.g., Bayley et al., 1966; Larue, 1981; Mattson and Cambray, 1983). This is an important determination, affecting aspects of regional and interregional correlation on a significant scale (e.g. Ojakangas, 1988).

This study focuses on the bulk and mineral chemistries of the Fern Creek Formation and Sturgeon River Quartzite exposed along an access road to a hydroelectric dam located about 3 km northeast of Loretto, Michigan. The purpose is to further evaluate the glaciogenic vs. fluvial origins of the Fern Creek Formation, and to characterize the materials to constrain possible source areas.

Fern Creek rocks are dominated by quartz, sodic plagioclase, K-feldspar, antiperthite, and micas of di- and trioctahedral composition. Sturgeon River is predominantly quartz with minor illite.

Zircon, tourmaline, fluor-hydroxy apatite, pyrite, rutile, fluorite, monazite, huttonite and a fluor-hydroxy REE mineral occur in the Fern Creek Formation. Zircon and tourmaline dominate in the Sturgeon River Quartzite.

The tourmaline compositions vary systematically with vertical position throughout the Fern Creek/Sturgeon River sequence. This suggests a gradual denudation of the source area over an extended length of time.

Bulk chemistries for the Sturgeon River Quartzite are consistent with an origin as a well sorted sediment in a nearshore marine environment. Fern Creek chemistries are typical of unsorted materials that have not undergone hydraulic differentiation, and are similar to chemistries from the underlying Carney Lake Gneiss.

REE distributions are highly variable in the Fern Creek Formation, ranging from nearly flat (normalized to PAAS) to extremely steep (e.g. chondrite normalized La/Yb of 101.5). These distributions result from enrichment in LREE- and Th-rich minerals.

The bulk chemistry and presence of REE minerals are consistent with proximal derivation from the underlying (pegmatite-rich) Carney Lake Gneiss. The trends in tourmaline composition suggest association with a process capable of deep erosion over an extended period of time. The similarity of the Fern Creek to stratigraphically equivalent rocks at some distance north suggests a process of significant areal extent. Taken together, these results strongly support the origin of the Fern Creek Formation as a proximal till derived from the underlying gneiss.

References

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RESULTS OF REGIONAL TILL SAMPLING IN THE WESTERN PART OF THE SHEBANDOWAN GREENSTONE BELT, NORTHWESTERN ONTARIO

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A project of Quaternary geological mapping and regional till sampling was undertaken over the western part of the Shebandowan greenstone belt during the 1999 field season. Quaternary mapping helped to characterize the surficial materials present within the study area and to reconstruct the ice flow history associated with these deposits. This information provided a framework by which the regional materials compositional datasets could be interpreted. The regional sampling program provided information on the background concentrations of various elements in till as well as on the number and character of gold grains and base metal indicators in till.

The study area contains a relatively simple record of Quaternary events. Most deposits were laid down during the final retreat of ice from the area. Ice flow indicators suggest a consistent pattern of flow towards the south across the eastern half of the study area, becoming more westerly towards the west. Till cover is generally thin and discontinuous over most parts of the study area. Thicker, more extensive till is present within Hagey, Conacher and Blackwell townships. Till samples collected from these townships are less representative of local geology than are samples collected from areas of very thin till. Geochemical and mineralogical interpretations should consider these local variations in till character.

The till sampling program has clearly identified a number of precious and base metal exploration targets within the western Shebandowan greenstone belt. Higher density follow-up sampling surveys are recommended for these areas to determine the significance of the anomalies and more precisely define potential source rocks. The regional character of this survey will assist with the interpretation of local, property-scale geochemical datasets by placing results into context with respect to regional background. The results of this survey clearly support the use of till compositional surveys for mineral exploration. The approach for follow-up sampling programs will be dictated by the type of mineralization sought and the local conditions within a given property.

NOMARSKI DIC MICROSCOPY AND STRUCTURAL STATE ANALYSIS OF PLAGIOCLASES FROM THE DULUTH COMPLEX, MINNESOTA

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Nomarski Differential Interference Contrast (DIC) and structural state XRD analyses were carried out on samples of Duluth Complex Anorthositic Series rocks. Nomarski DIC is a reflected light technique which uses a double-crystal prism to split plane-polarized light to produce a dark-light shading that highlights microrelief. To use the method on mineral specimens, polished sections are etched in acid to produce microtopography. Anderson (1983), Pearce and Kolisnik (1990), and Pearce (1994) discuss the importance of interference imaging in showing that high-resolution mineral zonation patterns, that are correlatable with varying An content, record complicated dissolution and reaction events that occurred during crystal growth.

Polished block and thin sections were prepared from three samples of the anorthositic series taken near its contact with the Duluth Layered Series, along Skyline Parkway in Duluth above Oneota Cemetery (Stop 1-5 of Miller, 1995). Sample 1 is an inclusion containing more than 95% plagioclase; sample 2 is the host gabbroic anorthosite, and sample three is from the outcrop used for zircon age dating (Paces and Miller, 1993). Polished thin sections were prepared on orthogonal axes to expose a variety of crystallographic orientations, etched in 48-50% HBF₄ for approximately seven minutes (adapted from the method of Anderson, 1983), and then imaged using a Nomarski mirror cube and prism slider on an Olympus BX-60 petrographic microscope.

Although some oscillatory zoning was observed, the most common zoning observed was patchy. This type of zoning could be considered a hiatus type of discontinuity as defined by Castro and de la Rosa (1994). Irregular zoning of plagioclase is common in the Anorthositic Series (Miller and Weiblen, 1990) and could indicate significant disruptions of the crystallizing surface due to dissolution and reaction events as the crystal mush moved from deep to shallow chambers.

Plagioclase structural analyses were carried out on the three samples plus one additional plagioclase separate from the Duluth Anorthositic Series (Sample D-12) and one from the Gabbro Lake area (sample BL-27). Samples were crushed and plagioclase was hand-picked, powdered, and diffraction patterns collected on a Philips Automatic Vertical Diffractometer at the Materials Characterization Laboratory at NDSU. Scans were made from 6.0 to 65 degrees 2 θ using a step of 0.02° 2 θ , Cu K α radiation (λ = 1.54184 angstroms), a diffracted

beam monochrometer, and a sealed proportional counter. Patterns were matched to a plagioclase in the PDF reference file and refined using Garvey's (1986) implementation of the program of Appleman and Evans (1973). Refined $\Delta 131$ and γ values were used to determine the structural state based on figures from Kroll (1983). Despite the potential difficulties with refining zoned minerals, the results (with the exception of sample 3-99, for which An content is yet to be measured) indicate that all the samples are in "low" (low-temperature, or ordered) structural state (Table 1).

sample	1-99	2-99	3-99	BL-27	D-12
γ°	90.180 (+/- 0.084)	90.247 (+/- 0.204)	90.299 (+/- 0.130)	89.843 (+/- 0.190)	90.213 (+/- 0.218)
An	65*	62*	n.m.	55	63

Table 1. Refined gamma and An values for plagioclase separates of Duluth Complex Anorthositic Series rocks. *from Miller (1995); n.m. not measured. Errors reported as two standard deviations, because no internal standard was used.

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Acknowledgements: Dean Grier guided us in carrying out the plagioclase structural analyses. BSE gratefully acknowledges financial support from ND EPSCoR through NSF grant #OSR-9452892.

Wind or Water?

Paleoenvironment of the Proterozoic Hinckley Sandstone, Northeastern Minnesota

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The Proterozoic Hinckley Sandstone is a mineralogically mature, fine-grained quartz arenite representing late stage Keweenawan rift fill sedimentation. Previous work (Tryhorn & Ojakangas, 1972) interpreted the Hinckley Sandstone as a shallow-water lacustrine deposit. Recent recognition of adhesion structures, formed by sand blown onto a damp surface, suggest that this formation may be partially eolian (wind-deposited). The purpose of this project was to reevaluate the environment(s) of deposition of the Hinckley Sandstone.

The study area is located in Pine County, MN, near the town of Sandstone, where five sections along the Kettle River were measured and described in detail. Four major facies were identified: planar-bedded sandstone (PS), cross-stratified sandstone (CSS), trough cross-stratified sandstone (TCS), and pebbly trough cross-stratified sandstone (PTS). The planar-bedded facies comprises a complexly interbedded sequence of crinkly and mottled strata, preserved ripple forms, and packages of thin (2-6 mm.), planar, inversely graded laminae. Crinkly and mottled strata are interpreted as adhesion structures (Hunter, 1973, 1980). Ripples have low ripple indices (<10) and steep, normally graded foresets, indicating a subaqueous origin (Hunter, 1977). Planar laminae are identified as climbing wind-ripple laminations (Hunter, 1977). Therefore, the planar-bedded facies represents an environment where conditions alternated from wet to damp to dry. Fine grain size, large set size, and the compound nature of large sets suggest a large-scale eolian dune origin for the cross-stratified sandstone facies. In addition, wind-ripple and adhesion lamination were identified in tangential dune apron toe-sets. Trough cross-strata and pebbly trough cross-strata facies contain predominantly medium-grained sandstone; pebbles up to 4 cm. are common in the pebbly trough cross-stratified facies. Adhesion and wind-ripple laminae are absent in these relatively small (up to 2 m. wide and 20 cm. thick), simple trough cross-strata. Coarse grain size and nature of strata suggest a subaqueous origin for these facies.

Exposures of the Hinckley Sandstone are incomplete and widely separated, limiting detailed correlation of sections. The thickest exposure measures 30 m., whereas a thickness of 150 m. for this formation is reported from a well in the area (Morey, 1977). However, using a regional structural dip of 5° or less, (Tryhorn and Ojakangas, 1972) the measured sections stack to give a sediment sequence that alternates from deposition in subaqueous to subaerial and back to subaqueous conditions several times. Small (mm.- to cm.-scale) extensional faults and cm.- to dm.-scale fluid-escape structures are associated with the subaqueous to subaerial transition. This vertical sequence suggests a rift setting with a shifting mosaic of eolian and fluvial, and possibly lacustrine, environments.

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Some factors that control the distribution of mercury in the near-surface environment of Isle Royale National Park, Michigan—earth, wind, and fire

W.F. Cannon, U.S. Geological Survey, Reston, VA

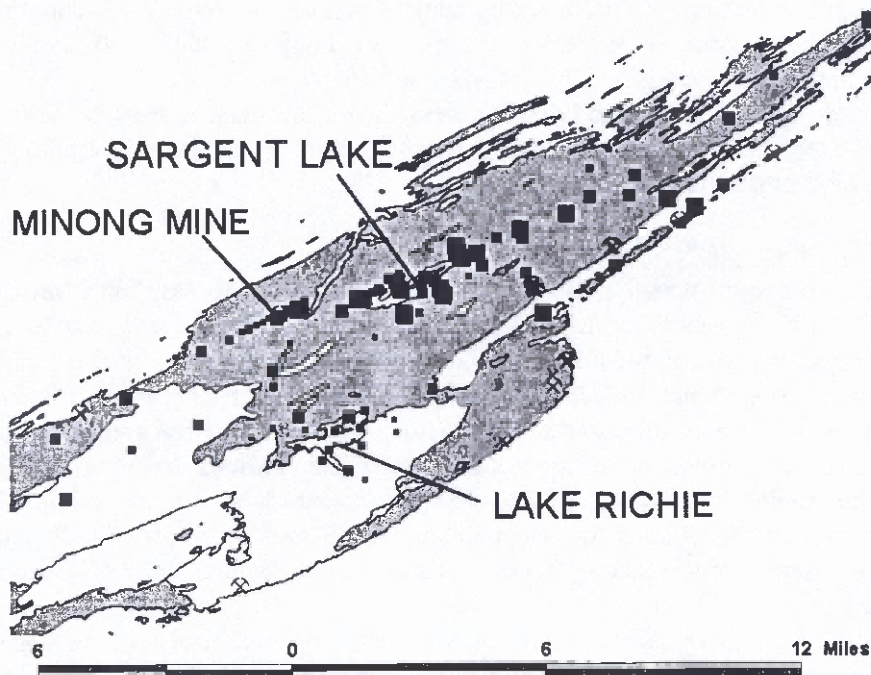
L.G. Woodruff, U.S. Geological Survey, St. Paul, MN

The concentration of mercury in soils on Isle Royale is highly variable in response to many factors whose affects and interplay are poorly understood. Our studies during the past three years have helped to clarify some of them. Interest in mercury distribution on the island was heightened in the mid 1990's when potentially dangerous mercury levels were discovered in game fish from six of the island's inland lakes. Because these six lakes were clustered in the north central part of the island, whereas lakes on other parts of the island showed lower mercury levels in game fish, we initially suspected that previously unrecognized bedrock mercury concentrations within the watersheds could be a cause. Small native copper deposits with significant mercury content are distributed throughout the island. To test this hypothesis we sampled soils around the Minong Copper Mine, the largest of the 19th century mining operations, and within the watershed of Sargent Lake, one of the mercury impacted lakes. Results presented last year (Cannon and Woodruff, 1999) showed that a bedrock source for mercury to the impacted lakes is unlikely. The Minong copper deposit produces a very pronounced copper anomaly in soils, but a comparable anomaly is absent within the Sargent Lake watershed. We did find, however, that a-horizon soils in the Sargent Lake watershed contain very high mercury concentrations. Because a bedrock source is unlikely we concluded that mercury concentrations were largely from airborne deposition.

Additional sampling and analyses have been conducted in the past year to address the question of why mercury concentrations are so variable in soils if the source of mercury is atmospheric pollution. There is a very high correlation between organic carbon in soils and total mercury content ($R=0.9$). Thus, it appears that factors that control carbon sequestration in soils also control mercury sequestration. One factor that could influence both is the history of forest fires. During a fire much of the carbon on the forest floor and in surface soil layers may be burned, thus liberating adsorbed mercury as a gas or fine particles that would be transported out of the area. After a fire, the gradual accumulation of organic carbon and mercury can require decades or longer to reestablish pre-fire concentrations. A large portion of Isle Royale burned in 1936, including part of our study area, whereas the remainder of our study area has not burned in historic times. Soils within the 1936 burn area invariably have low carbon and mercury content. All samples are below the mean concentration for the island. Some soils outside of the burn have comparably low values but most are significantly higher. Further sampling is being conducted to seek additional confirmation of the importance of this 64-year-old fire to current mercury distribution.

Finally, the distribution of mercury in geological materials as a possible factor in controlling mercury accumulation in the aquatic food web needs to be addressed. High mercury concentrations in game fish are the end result of successive accumulations through various steps in the food web. Mercury concentrations in game fish tissue may be

as much as one million times higher than in the ambient lake water. Furthermore, mercury enters the food web as an organic compound, mostly dimethyl mercury, rather than the more common inorganic forms. As a result, many researchers discount the concentrations of mercury in the terrestrial environment as a factor controlling mercury in fish. Rather, the efficiency of methylation processes within a lake and its watershed and complexities in the food web are commonly cited as causes for widely variable mercury content of fish between nearby lakes. Our results now show that there are much higher mercury concentrations in soils in the watersheds of Sargent Lake (high mercury in fish) than in soils around nearby Lake Richie (low mercury in fish). Although these results address only two lakes, we suggest that it would be premature to discount variations in mercury in watershed soils as a factor in determining the intensity of mercury accumulation in related aquatic ecosystems.



East half of Isle Royale. Relative mass of mercury (concentration x soil thickness) in a-horizon shown by black squares. White area was burned in 1936 forest fire. Native copper mines and prospects shown by pick and hammer symbol.

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A SEQUENCE OF FOLDING AND DEXTRAL TRANSPRESSION IN THE SEINE RIVER CONGLOMERATES.

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GEOLOGICAL INTRODUCTION

The Superior Province is comprised of approximately east - west trending subprovinces that are defined by lithological contrasts, metamorphic grade, and structural boundaries (Card and Ciesielski, 1986). A popular tectonic model for this province is the successive accretion of island arcs and their associated sediments (Hoffman, 1989).

This study focuses on the boundary between the metavolcanic Wabigoon and the metasedimentary Quetico subprovinces near Mine Centre, Ontario. The Quetico contains mostly amphibolite facies metasediments, and the Wabigoon contains greenschist facies metavolcanics. Distinctive rocks found along this boundary are the Seine River Metasedimentary Group including the polymictic Seine River conglomerates. From stratigraphic evidence, the Seine River conglomerates formed late following the deposition of the volcanic sequences (Poulsen et al., 1980). Preliminary attempts at absolute dating have confirmed this (Davis et al., 1989).

Previous structural work along this boundary described a dominant subvertical foliation transecting large folds (Poulsen, 1986; Tabor and Hudleston, 1991). These features are interpreted to have formed during dextral transpression.

STRUCTURAL INTRODUCTION

The term "transpression" was first introduced by Harland (1971) to describe motion that is obliquely convergent, or motion partitioned into both convergent and strike-slip. In Harland's original paper, he described the development of folds and strike-slip structures due to oblique convergence. A specialized case of transpression was introduced by Sanderson and Marchini (1984). This idealized definition of transpression has been used to describe homogeneous deformation consisting of orthogonal simple shear and pure shear components with constant volume and confined deformation boundaries, possibly corresponding to the strain in deep ductile shear zones that accommodate oblique convergence. The dominant foliation along the Wabigoon - Quetico boundary seems to be related to this more specific type of transpression based on the flattening fabrics and asymmetric features indicating simple shear in the subhorizontal plane.

One of the questions addressed by this study is the relationship between the folds and the dominant foliation. Clearly, it has been demonstrated that folds can form in transpression Harland (1971). Are the folds at this boundary consistent with the rest of the transpression fabric, or are they an earlier structural feature?

FOLIATION/ BEDDING INTERSECTIONS

The Seine Group has well defined bedding indicated by fine grained layers interbedded with the pebble conglomerates. In this analysis, the major fold in the Seine River conglomerates was recognized on the basis of structural facing between bedding and the dominant foliation (Shackleton's rule - see Borradaile (1976)). This fold is consistent with the observed "way up" indicators in the conglomerates based on graded bedding.

If this fold were to have formed as a result of the transpression, the foliation/ bedding intersections should be consistent throughout the field area. In fact, the plunge of the intersection varies throughout the field area. The intersection angle is generally small because both foliation and bedding are steep; however, locally the angle is quite large nearing 75° at the hinge. This suggests a more complex history, and that the folding occurred prior to the major transpressive event.

TECTONIC IMPLICATIONS

As described elsewhere in the Superior province, the sequence of initial folding followed by homogeneous transpression (and possibly later stage amplification of the strike-slip shear component along discrete shear zones) seems reasonable for the Wabigoon- Quetico boundary. It remains an interesting question whether the folds and the homogeneous transpression were two entirely abrupt, separate events or rather an evolution of structural styles during different stages of the same oblique collisional event.

The fact that the initial folding is seen in the Seine Group has important implications for the relative timing between this change in structural style and Seine deposition. Some researchers have suggested that the Seine Group could have been syntectonically deposited in pull-apart basins formed as a result of wrenching (Poulsen, 1986). The early folding of the Seine seems to indicate that it was deposited earlier in the deformation sequence, prior to at least some of the folding. Additionally, the overall geometry of the interconnected faults seems to indicate that during dextral wrenching, the Seine Group's "basin" would have been in a compressive rather than an extensional regime required of a pull-apart basin. This suggests that a different sedimentation/ tectonic model for the Seine Group is needed.

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A Hf isotopic study on zircons from the western Superior province

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U-Pb dating of zircon has provided some of the most important constraints on geological interpretations in the Superior province. Zircon also contains Hf, whose ^{176}Hf isotope can be used to infer older crustal provenance of the magma from which it crystallized. Early Hf studies by Corfu and Stott (1993, 1996) in the Uchi subprovince show a distribution of E_{Hf} values that range between depleted mantle and a 3.0 Ga crustal growth curve, reflecting contamination from the North Caribou terrane and supporting the model of an Andean-type tectonic setting. These studies used thermal ionization mass spectrometry, which is laborious and requires large quantities of zircon. The recent development of multi-collector inductively coupled mass spectrometry now permits precise measurement of Hf isotopic analyses on single zircon grains as small as 2 micrograms with analysis times on the order of 10 minutes per sample.

Using the Plasma54 instrument at the NERC lab, Hf isotopes were measured on dated zircons from 62 separate rock units in the western Superior region plus 25 detrital zircon grains from the ca. 2700 Ga Quetico metasediments and pre-2800 Ma quartz arenites. The mass spectrometer analyses were done over a four day period. This expands the available Hf database in the transect area by a factor of four.

Most data from the SW Wabigoon subprovince cluster tightly around a depleted mantle E_{Hf} value of +6.5. This confirms that assemblages south of the Winnipeg River subprovince were magmatically emplaced in an oceanic environment. Analyzed zircons from the Sturgeon-Savant area show a trend of increasing contamination by older crust with younger age (decreasing E_{Hf} down to +2).

Younger plutons and volcanics from the central Wabigoon subprovince (2693-2750 Ma) mostly scatter around values of $+4 \pm 1$, showing the possibility of slight contamination by older crust. Zircons from the older 3000 Ma old rocks in the Lumby Lake belt cluster tightly around a depleted mantle value (at 3.0 Ga) of +5.5. Zircons from ca. 2.9 Ga plume-derived rocks give slightly more enriched values down to +4. The results from Lumby Lake overlap with those from similar aged rocks in the North Caribou Lake area of the Sachigo subprovince, supporting the suggestion that the Lumby Lake and North Caribou terranes are correlative.

The Hf data field from the Wabigoon and Sachigo subprovinces overlaps closely with that of Corfu and Stott (1996) from the Uchi subprovince. In contrast zircons from the Winnipeg River subprovince are noticeably more enriched, with E_{Hf} values of about 0 to -2 over an age range of 2721 Ma to 3225 Ma. An E_{Hf} value of -2 value found on 3.2 Ga zircons from the Cedar Lake gneiss implies a ca. 3.5 Ga crustal protolith, in agreement with results of Nd whole rock isotopes (Henry et al. 1997).

A single analysis from the widespread 2722 Ma volcanics in the Shebandowan belt shows a depleted signature, as does a 2726 Ma volcanic from the Melchett Lake belt, in the middle of the English River subprovince. However, 2723 Ma volcanic zircons from the Separation Lake greenstone belt, which may underlie English River metasediments, show a

more enriched value of -2, suggesting that it is contaminated by much older Winnipeg River-type crust.

Results on detrital zircons from quartz arenites in the North Caribou terrane generally overlap the data field from rocks in this area. An analysis from 3250 Ma old zircon in the Jutten quartz arenite in the northern Wabigoon subprovince shows still older contamination (E_{Hf} of 0), suggesting that 3.0 to 3.3 Ga detrital zircons in this unit were derived from the adjacent Winnipeg River subprovince. Ca. 3.2 Ga zircons from the Quetico metasediments also show enriched values down to -3, while the youngest zircons at ca. 2.7 Ga show variable enrichments from +5 to +0, again suggesting a source partially in the Winnipeg River subprovince.

The general coherence of the highest E_{Hf} values at ca. 2.7 Ga and 3.0 Ga provides reasonable constraints on the evolution of the depleted mantle reservoir during the late Archean. These results agree with the linear growth trend defined by other Hf measurements from younger rocks and from early Archean rocks in Greenland (Vervoort and Blichert-Toft 1999). They give evidence for a major depletion of the mantle at or before 4.0 Ga. If continental crust was the complimentary enriched reservoir, this implies that such crust was of an extent comparable to the present during the early Archean. Otherwise, the enriched reservoir may have been oceanic crust that was subducted and stored in the deep mantle until the end of the Archean.

Continuing Hf isotopic studies on precisely dated zircons promise to be a powerful tool for resolving local and global problems in Earth history.

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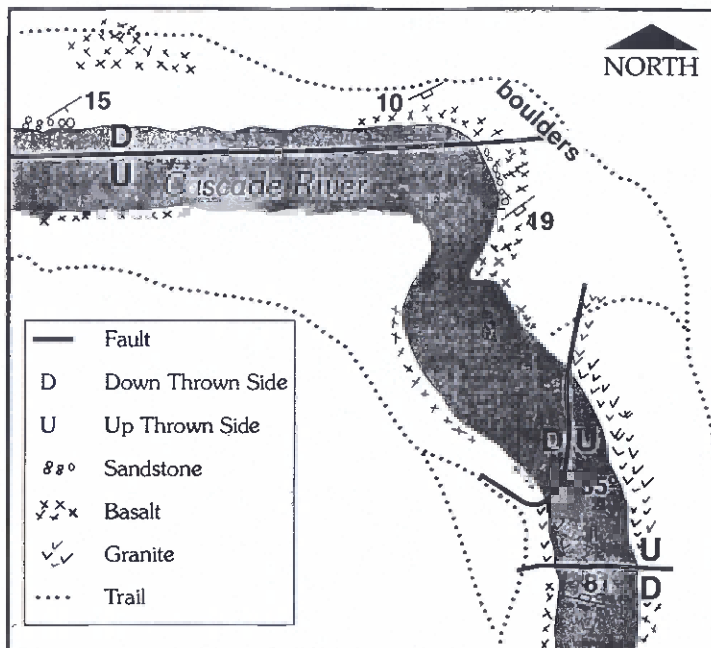
MYSTERY FAULTS OF THE CASCADE RIVER, NORTH SHORE, OR, WHAT IS THIS GRANITE DOING HERE?

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The Cascade River in Cook County, MN, exposes a homoclinal section about 13 km long across normal-polarity rocks of the North Shore Volcanic Group. With an average dip of about 12 degrees, this amounts to a thickness of about 2.4 km. In its lowest mile and a major tributary, it cuts across several faults that involve the great, cuesta-forming Terrace Point basalt flow and the thick, underlying Good Harbor Bay sandstone.

At the top of the cascades, the conformable contact between the big red sandstone and the overlying flood basalt flow, also visible four miles to the east at the big Good Harbor Bay highway cut, is dropped down to the north a few feet along a high-angle, east-west fault. As the river starts to enter the gorge and plunge down the cascades, the top of the sandstone can be seen under the basalt. But less than 100 m into the gorge, the basalt is interrupted by a remarkable breccia of pink, medium-grained granite that occurs in apparent fault contact with the volcanic rocks. Locally, fragments of basalt and perhaps sandstone are caught up in the breccia, but most of it is uncontaminated granite. On the downstream side, abundant joints in the adjacent basalt imply a steep fault contact dipping upstream, but it is covered. On the upstream side, the bounding fault apparently dips much more gently downstream, implying a wedge of granite emplaced mechanically into the lava flows. A fault contact a kilometer or so to the northeast between the sandstone and a rhyolite may be related to this event.

There are two conceivable sources for this granite, which must be far from its original site of crystallization. If it is Keweenawan, and related to the roof zone of the Duluth Complex that is exposed up-dip (inland) at Eagle Mountain, it would have moved upward at least 2.4 km. Otherwise it could be part of the Archean basement, in which case it would have come up much farther, perhaps 10 km. It is medium-grained, hypidiomorphic with minor micrographic patches and its ferromagnesian silicate is Fe-rich biotite, which is rare in Keweenawan granites. Petrographically it is not a good match for either the Eagle Mountain granophyre or typical Archean granitic rocks of the region. Its abundant zircons should solve the problem of where it came from, but not how it got to its present position.



Geologic sketch map from Green, 1996, Geology on Display: Geology and Scenery of Minnesota's North Shore State Parks, MN Dept. of Nat. Resources, St. Paul

PETROGENESIS OF GRANITIC ROCKS OF THE DUNKA RIVER REGION, EASTERN MESABI RANGE, MINNESOTA

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Middle Proterozoic felsic igneous rocks are exposed throughout the Midcontinent Rift (MCR) and the eastern Mesabi Range of northern Minnesota. Many of these are considered to be Keweenawan (1,100 Ma) in age. However, recent studies suggest that some early Middle Proterozoic felsic magmatism may have occurred in the region as well (Phillips et al., this volume). To better understand the history of felsic magmatism in northern Minnesota, samples from the Dunka River Region, which is situated along the base of the Duluth Complex, have been collected and studied. Felsic rocks that intrude gabbros of the Dunka River Region have coarse graphic textures, and are chemically distinct from granophyre complexes in the Midcontinent Rift.

Granitic rocks were collected from along the eastern Mesabi Range between Babbitt and Aurora, Minnesota. Granite with coarse graphic texture was collected from stockpiles within the mining operations along the contact between metamorphosed Biwabik Iron Formation and gabbro of the MCR. These granites occur as small dikes within gabbro and iron formation (Strandlie, pers. communication). They are commonly pegmatitic, and are composed of potassium feldspar or sodic plagioclase (40-50 %), quartz (35-45 %), and biotite (5-10 %). Feldspars are variably altered to clay minerals and biotite is altered to chlorite. These graphic granites are mineralogically and texturally comparable to some felsic granophyres of the Midcontinent Rift (Kennedy et al., this vol.). Other granitic rocks were collected from nearby outcrops of the eastern margin of the Archean Giants Range batholith for comparison. The Archean granites are fine- to medium-grained, and consist of plagioclase (20-40%), amphibole (<15%), quartz (10-40%), potassium feldspar (5-20%), biotite (5-10%), and Fe-Ti oxides (<5%), and commonly exhibit strained quartz and weakly foliated textures. These granites are texturally and compositionally similar to granites of the western Giants Range batholith (e.g., Boerboom and Zartman, 1993).

The graphic granite dikes from the Dunka Pit are characterized by a greater silica content ($\text{SiO}_2=70.8\text{-}78.7$ wt. %) than is observed in MCR granophyres (66-76 wt. %; Kennedy et al., this vol.) and the Aurora Sill syenites (54.6-60.7 wt. %; Phillips et al., this vol.). Potassium, sodium, and calcium concentrations of the granite dikes ($\text{K}_2\text{O}=2.98\text{-}5.16$ wt. %; $\text{Na}_2\text{O}=3.20\text{-}6.48$ wt. %;

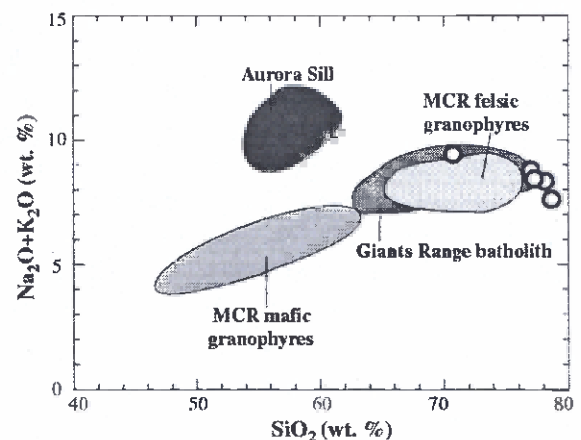


Figure 1. Plot of $\text{Na}_2\text{O}+\text{K}_2\text{O}$ (total alkalis) versus SiO_2 comparing Dunka graphic granites (open circles) with rocks from the Giants Range batholith (Boerboom and Zartman, 1993), the Aurora Sill (Phillips et al., this vol.), and granophyre complexes of the MCR (Kennedy et al., this vol.).

CaO=0.28-1.09 wt. %) are similar to those of the MCR granophyres and the Aurora Sill (Figure 1). However, most of the graphic granites have high Al_2O_3 concentrations and are peraluminous, similar to those of the Aurora Sill; MCR granophyres are peraluminous to metaluminous. The graphic granites also have less TiO_2 than rocks of the MCR and the Aurora Sill. The graphic granites are compositionally similar to those of the Giants Range batholith, although they have slightly higher SiO_2 concentrations (Giants Range SiO_2 values range from 52.9-73.6 wt. %).

On trace element diagrams (e.g. Zr/TiO_2 vs. Nb/Y) the graphic granites are distinct from Aurora Sill syenites (Phillips et al., this vol.), but plot with the Duluth Complex granophyres (Kennedy et al., this vol.). However, whereas major element concentrations of Dunka graphic granites are similar to those of felsic rocks of the MCR granophyre complexes, their trace element compositions are more similar to those of mafic rocks of the MCR granophyres. A plot of Nb vs. Y (Figure 2) reveals the depletion in graphic granites of both Nb and Y with respect to MCR granophyres and Aurora Sill syenites. Furthermore, the greater Y/Nb and Th/Nb ratios of the graphic granites are most similar to those of the Giants Range batholith and suggest that these rocks contain a more significant crustal component than do the MCR granophyres and Aurora syenites.

Graphic granites of the Dunka River Area are similar in mineral and major element compositions to felsic granophyres associated with the Midcontinent Rift. However, the low trace element concentrations of the Dunka graphic granites are more similar to the mafic rocks of the granophyre complexes. Therefore, we conclude that the graphic granites of the Dunka Region are unrelated to the other felsic granophyres of the Midcontinent Rift and to the Aurora Sill. Alternatively, they might be partial melts of country rock along the base of the Duluth Complex. The chemical similarity between the Dunka graphic granites and the Giants Range batholith granite suggests that partial melting of Archean granites could have produced the melts for the graphic granite. Alternatively, the graphic granites might be the melting products of nearby argillite, argillaceous siltstone, and fine-grained feldspathic graywacke of the Virginia Formation (e.g., Morey, 1972).

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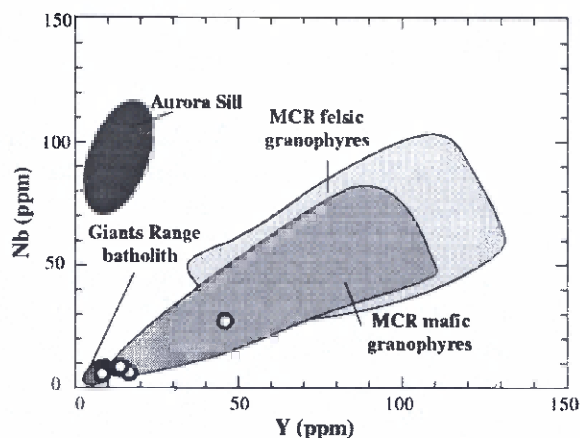


Figure 2. Plot of Nb versus Y comparing Dunka graphic granites (open circles) with other felsic rocks of northern Minnesota; see Figure 1 for data and references.

Copper Mineralization in the Pyroxene Hornfelsed Archean Giants Range Batholith Footwall of the Keweenaw South Kawishiwi Intrusion, Duluth Complex, NE Minnesota - Archean or Keweenaw Mineralization?

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Copper sulfide mineralization in the Archean (~2.7 Ga) Giants Range Batholith (GRB) footwall of the South Kawishiwi intrusion (SKI) of the Keweenaw (1.1 Ga) Duluth Complex (DC) of northeastern Minnesota was first discovered by exploration companies drilling in the 1960s and 1970s, and was recently reported in outcrop in the Spruce Road area (pers. com., E. H. Dahlberg, 1998). The Cu mineralization was first described by Bonnicksen et al. (1980) and further described by Severson (1994). According to Severson (1994), the copper mineralization occurs as disseminated sulfides within the uppermost 330 ft. of the GRB, although in some drill holes the first 100 ft. may be barren. Chalcopyrite is the dominant sulfide. However, in the overlying SKI rocks pyrrhotite is the dominant sulfide. Also, at or just above the basal contact of the SKI and within the upper 100 ft. of the GRB, semi-massive to massive sulfides can occur, e.g., drill holes BL-95-1, K-1. These sulfides are generally pyrrhotite-rich, and may have Ni>Cu values exceeding 1% Ni and/or Cu. Severson (1994) suggests, based on the linearity of the drill holes that contain sulfides in the GRB, that these drill holes define two northeast-trending belts or faults. Also coincident with these linear zones are elevated platinum-group element (PGE) and Cr mineralization in the overlying SKI. Bonnicksen et al. (p. 563, 1980) state these Cu-enriched zones in the GRB "probably resulted because fractional crystallization caused Cu enrichment in the melts as they trickled downward through a decreasing thermal gradient beneath the complex". A similar model for Cu-PGE mineralization has been proposed for the footwall mineralization in the Sudbury Complex (Naldrett, et al., 1999).

In 1997, INCO's U.S. subsidiary, American Copper & Nickel, began a new exploration program on their Spruce Road Cu-Ni deposit east of Ely, MN. Based on their previous drilling, INCO identified fifteen $\geq 1\%$ copper intercepts in the footwall, which suggested footwall copper exploration potential. Recently at Spruce Road, several 1960-era drill holes were found to be open for geophysical surveys. Two drill holes (13648, 34889) were probed using a 3D Borehole Pulse EM geophysical survey, and in hole 13648, a footwall conductor was identified at 375m (1,230 ft.; Ravenhurst, 1997). In 1999, Wallbridge Mining Company, in joint venture with INCO, drilled DDH WM-1 to 1,754 ft. At 183 ft. and 330 ft. beneath the basal contact of the Duluth Complex (919 ft.), footwall copper mineralization was intersected, i.e., 79.5 ft. of 0.17% Cu, which includes 1.1 ft. of 1.91% Cu and 10.5 ft. of 0.55% Cu. Nickel, PGEs, and Au are minor constituents.

The footwall to the DC is generally composed of felsic, intermediate, mafic, hybrid rocks, and scattered hornfelsed inclusions (Severson, 1994), some or all of which may be related to the GRB. In the Spruce Road area, Green (1970) reports two types of granitic rocks, i.e., porphyritic and non-porphyritic. Both types are composed of hornblende-biotite adamellite, monzonite, granodiorite, and several mafic rocks. All rock types are cut by a variety of dioritic and gabbroic dikes, which may have been metamorphosed by the SKI. In the vicinity of the Spruce Road Cu-Ni deposit, the GRB has been contact metamorphosed (Green, 1970). The GRB rocks intersected in WM-1 include several of these rock types, e.g., porphyritic quartz monzonite, quartz monzonite, granodiorite, monzonite, possible Archean Knife Lake Group hornfels inclusions, as well as melanorites and norites, which are less certain in origin. All of these rock types have undergone pyroxene hornfels (opx+cpx+amphibole) contact metamorphism. Of primary interest, however, is mineralization within the footwall melanorites/norites, and the footwall GRB itself.

The melanorites and norites have sharp intrusive contacts with the granitoid rocks, and include rounded fragments of them. Petrographically, the melanorites are composed of opx and cpx (30-60%), amphibole (~1-80%), zoned and unzoned plagioclase (10-60%), biotite (4-8%), minor quartz (1-3%), apatite (<1%), muscovite (<1-3%), oxides (<1-2%), and sulfides (<1-3%). Opx and cpx are subhedral to euhedral and crystallized early. Amphibole generally rims the pyroxenes, and in some instances corrodes the pyroxenes producing anhedral crystals. Anhedral to subhedral, zoned

and unzoned plagioclase may show undulose extinction, occur as equant grains, and are often altered to clay minerals. Anhedral to subhedral flakes of biotite follow the crystallization of plagioclase and can be porphyroblastic. Quartz is the last silicate to crystallize. Apatite occurs as euhedral rods, both very early and late in the sequence. Oxides (magnetite > ilmenite) and sulfides are last to crystallize. The oxides and sulfides are often associated with alteration of the pyroxenes to biotite, muscovite, talc (?), and chlorite (?) along fractures and along the rims in the opx. The sulfides, in order of appearance, are millerite, sphalerite, and bornite and/or chalcopyrite. The sulfides also occur as interstitial to net-textured grains that surround opx. The melanorites also contain net-textured magnetite.

A similar sulfide and silicate mineralogy occurs in the footwall host rocks. These rocks can have feldspar phenocrysts with a plagioclase matrix and minor quartz ($\leq 5\%$), amphibole, opx, biotite, oxides (magnetite, ilmenite), and sulfides (chalcopyrite, bornite, millerite, pentlandite, sphalerite). The sulfides occur as blebs and discontinuous veins, generally associated with biotite, plagioclase, opx, $\pm$ amphibole, $\pm$ quartz, and oxides. The plagioclase in these zones is equant and equigranular, and exhibits sutured contacts with the larger plagioclase.

The copper mineralization in the granitoid and noritic rocks have Cu:Ni ratios of 8-32:1, compared to the 3.3:1 in the overlying DC. The Pd:Pt ratio in these rocks is 1-15:1, compared to the 3:1 in the overlying DC. Data from Severson (1994) on other footwall intercepts give Cu:Ni and Pd:Pt ratios of 2-9:1 and 2-7:1, respectively, indicating that Cu is enriched, and Ni and PGEs are depleted in WM-1 when compared to other footwall samples. Comparison of Cu:Ni in all GRB samples indicates a tendency for Cu enrichment and Ni depletion with depth beneath the basal contact.

The origin of this mineralization opens new and exciting aspects in Duluth Complex geology. Possible emplacement scenarios include:

1) A relict of Archean emplacement. The model is supported by both sharp contacts and net-textured sulfides and oxides in the mafic rocks of the footwall.

2) Keweenaw fractionation of Duluth Complex sulfide. The observed depletion of nickel and enrichment of copper with depth below the footwall-Duluth Complex contact, and the association of net-textured and discontinuous vein sulfide with biotite-muscovite-talc(?) -chlorite(?) alteration support this possibility.

3) Proximity to a "feeder-dike" to the Duluth Complex. This case is supported by the presence of magmatic-looking high-grade sulfide intersections not unlike those from Voisey's Bay and Sudbury. These intersections are associated with mafic assemblages not normally part of granitoid intrusions.

Regardless of preferred genetic model, these recent developments indicate significant new exploration potential for the Duluth Complex.

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An Archean age argument is supported by : 1) sharp intrusive contacts with xenoliths of host rock in the melanorites; and 2) magmatic-looking net-textured sulfides and oxides in the melanorites. A Keweenawan argument includes the previous examples and is also supported by: 1) depletion of Ni and enrichment of copper with depth beneath the basal contact of the DC (as might be expected of a downward differentiating sulfide melt through fractures and faults); 2) association of net-textured and discontinuous vein sulfides with biotite-muscovite-talc (?) -chlorite (?) alteration; and 3) possible emplacement of a Keweenawan "feeder dike" to the DC. Evidence would include the presence of magmatic pyrrhotite-pentlandite-chalcopyrite mineralization not unlike that of the Sudbury and Voisey's Bay, as well as the association of mafic assemblages not normally part of the granitoid intrusions. In any event, the presence of Cu-rich mineralization well below the basal contact of the SKI (300-425 ft.) is interesting and suggests a new exploration potential for the DC.

Table 1. Footwall Copper Intersections in WM-1

Interval (ft.)	Feet (ft.)	Cu ppm	Ni ppm	Co ppm	Ag ppm	Au ppb	Pt ppb	Pd ppb
1102.0-1107.3	5.3	4872	237	15	2.7	54	59	152
1251.6-1252.7	1.1	19100	592	23	5.7	99	69	154
1251.6-1262.1	10.5	5496	421	22	2.7	43	23	69
1249.0-1328.2	79.2	1655	144	12	0.9	21	9	37

Results of $^{40}\text{Ar}/^{39}\text{Ar}$ laser microprobe grain-scale age mapping of muscovite from Precambrian bedrock of the southern Lake Superior region

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The results of over 100 conventional $^{40}\text{Ar}/^{39}\text{Ar}$ step-heating mineral ages collected in the 1990's from the southern Lake Superior region have greatly increased our understanding of the thermal and deformational history of the crust following the Paleoproterozoic Penokean orogeny. Step-heating experiments, however, may not effectively reveal the internal distribution of radiogenic argon within crystals, but instead can mask important details of the samples thermal history (Hodges et al., 1994, *Geology*; Hodges and Bowring, 1995, *GCA*). We compare results of previous conventional $^{40}\text{Ar}/^{39}\text{Ar}$ step-heating experiments on four muscovite grains with new results from *in situ* spot analyses using the Ar-ion laser microprobe (see table below; age in Ma, uncertainties at two sigma).

<u>Sample</u>	<u>Location</u>	<u>Step-heating age</u>	<u>Age gradient</u>
97CM7	Republic, MI	1716 $\pm$ 5 plateau	1707-1660
97CM13	Dunbar, WI	1366 $\pm$ 6 near-plateau	1373-1327
96DR8	Little Falls, WI	1614 $\pm$ 5 plateau	1652-1563
97DR7	Neillsville, WI	1518 total gas	1923-1414

The form of the age gradient of sample 97CM7 suggests incorporation of excess ^{40}Ar along the grain boundaries. Core spot ages of 1660-1680 Ma are consistent with a nearby biotite plateau spectrum age (Schneider et al., 1996, *CJES*). Laser microprobe results from the other three samples reveal varying degrees of age gradients (see Figure 1 for examples). Sample 96DR8, which yielded an excellent plateau age of 1614 $\pm$ 5 Ma, revealed a >90 m.y. age gradient. The weighted mean of the 10 spot fusion ages is close to the plateau age. Step-heating therefore appears to have homogenized age gradients present in this sample. The spectrum of sample 97CM13 gives a near plateau age of 1366 $\pm$ 6 Ma, but shows age increments generally increasing from 1334 Ma to 1383 Ma. *In situ* spot laser analyses allow us to verify the existence of an age gradient (from at least 1373 $\pm$ 12 Ma to 1327 $\pm$ 9 Ma) with significant clarity. Sample 97DR7 yielded a saddle-shaped age spectra with a minimum age increment of 1484 $\pm$ 2 Ma (Fig. 1). Ar-ion laser microprobe data reveals a spectacular 500 m.y. age gradient from core (oldest) to rim. The youngest ages preserved (down to 1414 $\pm$ 21 Ma) are obtained from what is probably a real grain boundary.

A difficult problem in interpreting $^{40}\text{Ar}/^{39}\text{Ar}$ age gradients is whether they formed during slow cooling or resulted from superimposed, episodic reheating. If the entire core to rim gradient of sample 97DR7 (along the center to south transect, Fig. 1) reflects simple slow cooling with volume diffusion, then the implied cooling rate is about 0.3 K/m.y. This rate is remarkably similar to the integrated cooling rate estimated for the Proterozoic terrain of the southwest United States (Hodges et al., 1994). However, consideration of the overall geologic context within which these dated samples exist suggests a more complex episodic thermal history. Case studies (i.e., Hames and Cheney, 1996, *Eos*) suggest that the form of detailed grain-scale 'chrontour' maps should help to distinguish between simple and more complex thermal histories. Whatever their mechanism of formation, the documentation of large and quantifiable age gradients in this study indicates promise for obtaining more detailed information about the Proterozoic thermal evolution of the southern Lake Superior region.

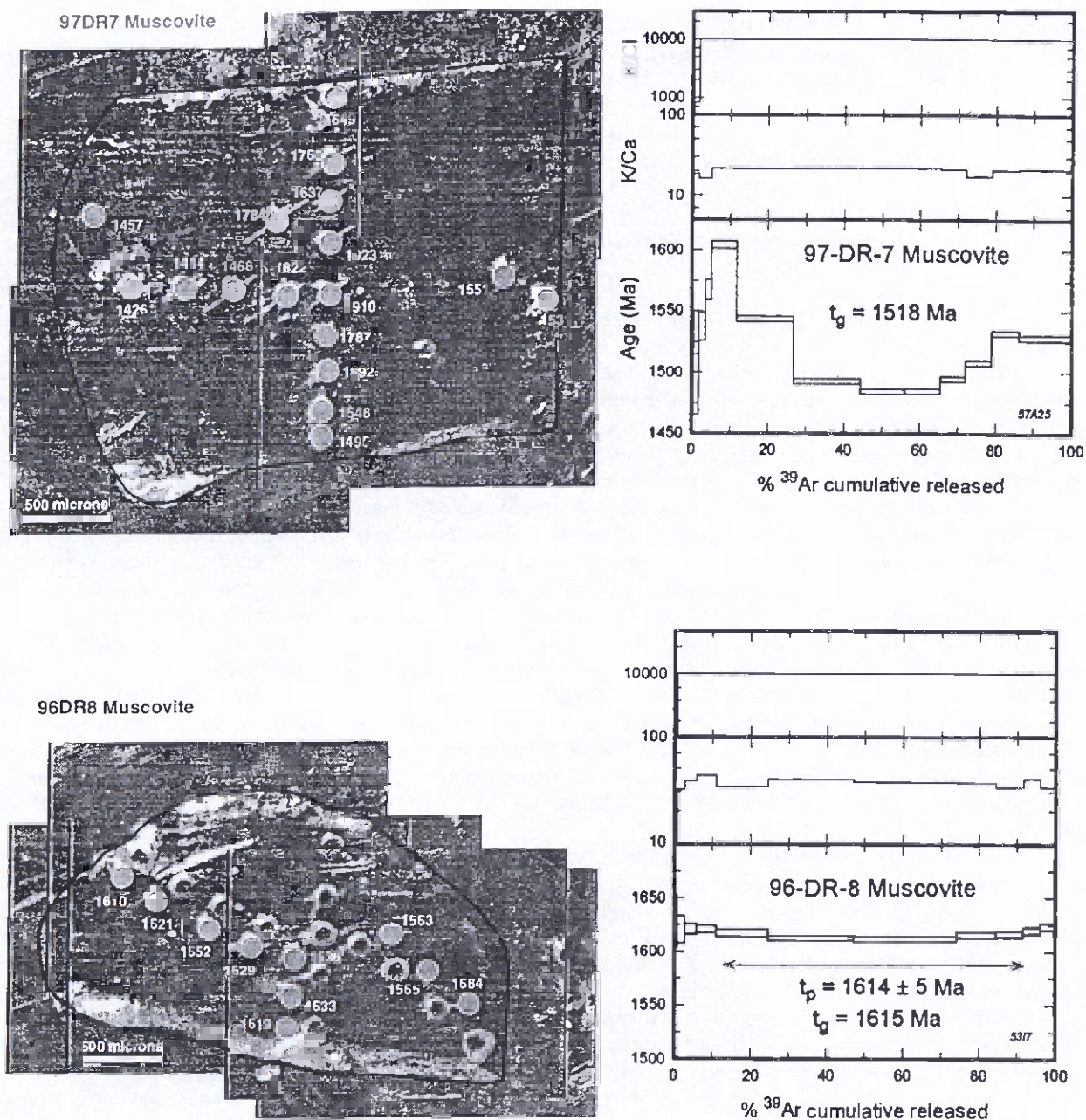


Figure 1. Spot fusion, single crystal age data (this study) and corresponding conventional incremental-release data (after Romano, Kent State M.S. thesis, 1999) for two muscovite samples from the southern Lake Superior region. 97DR7 is coarse muscovite from a muscovite gneiss of probable Archean age collected at Sylvan Lake west of Neillville, Wisconsin. 96DR8 is muscovite from a late pegmatite dike collected at Little Falls south of Eau Claire, Wisconsin. Grain images are video stills of individual (001) cleavage fragments (outlined), and the dots indicate the position of ca. 100 micron-diameter Ar-ion laser fusion pits, each labeled with its measured age (age uncertainties are variable but generally less than 10 Ma at two sigma). Unlabeled pits in 96DR8 produced too little gas for effective measurement.

**PRELIMINARY VOLCANOLOGY AND HYDROTHERMAL ALTERATION STUDIES AT THE
FIVE MILE LAKE, EAGLES NEST, AND QUARTZ HILL PROSPECTS:
IMPLICATIONS FOR VMS-STYLE MINERALIZATION IN NORTHEASTERN MINNESOTA**

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The Five Mile Lake, Eagles Nest, and Quartz Hill prospects occur in Archean metavolcanic and metasedimentary rocks the western half of the Vermilion District of northeastern Minnesota. The Five Mile Lake and the Eagles Nest prospects occur within the lower member of the Ely Greenstone Sequence, whereas the Quartz Hill prospect occurs within the Bass Lake Sequence (Peterson, 1999). Detailed diamond drill core relogging, petrography, and lithogeochemistry have been recently completed at these prospects (Hudak and Morton, 1999) to: a) better understand the geology (in particular, the physical volcanology) associated with these prospects; b) identify and evaluate the metamorphosed hydrothermal alteration mineral assemblages that occur at each of these prospects; and c) evaluate the potential for volcanogenic massive sulfide (VMS) and/or gold mineralization in these areas.

During our investigation, a total of eight diamond drill holes from the three prospects listed above were relogged and sampled for petrographic and lithogeochemical analysis. Four diamond drill holes from the Five Mile Lake prospect (SXL-1, SXL-2, SXL-3, and SXL-4), two diamond drill holes from the Eagle's Nest prospect (EN-4 and EN-7), and two diamond drill holes from the Quartz Hill prospect (QH-84-2 and QH-85-4) were relogged with an emphasis on identifying lithology, volcanic features and textures, metamorphosed hydrothermal alteration mineral assemblages, and syn-volcanic and post-volcanic fault zones. Sixty-four thin sections (33 from Five Mile Lake, 18 from Eagles Nest, and 13 from Quartz Hill) were evaluated for lithology, alteration types, primary and secondary textures, mineral modal analysis, and fragment modal analysis. In addition, thirty-eight lithogeochemical analyses (both major and trace element) were also performed (22 from Five Mile Lake, 10 from Eagles Nest, and 6 from Quartz Hill).

The Five Mile Lake region is composed of massive to amygdaloidal andesite/basalt lava flows and scoria-rich volcanoclastic deposits, locally quartz-phyric dacitic to rhyolitic lavas and flow breccias, and volcanoclastic and chemical sedimentary rocks. Quartz-feldspar porphyry and diabase dikes are also present throughout the volcanic and sedimentary sequence. Volcanic textures indicate that these rocks likely were formed within a deep water (>500meters) environment. Hydrothermal alteration minerals include epidote, iron-rich chlorite, magnesium-rich chlorite, and quartz (silicification). Stringer and semi-massive sulfide mineralization are associated with two distinct alteration assemblages: a) an early iron-rich chlorite - sericite - quartz assemblage, and b) an epidote - iron carbonate assemblage associated with late sulfide remobilization. The Five Mile Lake prospect appears to be a "Noranda-type" VMS system based on the criteria discussed by Morton and Franklin (1987).

Two diamond drill holes investigated in the Eagles Nest region comprise massive to amygdaloidal andesite/basalt lava flows and associated flow breccias/hyaloclastite, mafic to intermediate volcanoclastic sediments, Algoma-type mixed facies (sulfide, oxide, silicate) iron formations and associated chert horizons, interbedded siltstone and debris flow deposits, semi-massive to massive sulfide deposits, and rhyodacite to rhyolite tuffs and/or tuffaceous volcanoclastic sediments. Quartz feldspar porphyry intrusions and diabase dikes are also present. Volcanic textures suggest that the rocks in the area were also formed in a deep water (>500 meters) environment. A four meter thick intersection of pyrite-rich massive sulfide is overlain by approximately 2 meters (6 feet) of sulfide (py)-chert exhalite, which is overlain in turn by approximately 22 meters (73 feet) of mixed facies Algoma-type iron formation. The host and footwall rocks to the sulfide mineralization comprise sericite-, iron-rich chlorite-, kaolinite-carbonate- (dolomite and/or ankerite) and locally magnesium-rich chlorite-altered felsic ash tuffs or tuffaceous volcanoclastic sediments. Based on the volcanology and hydrothermal alteration present, the Eagles Nest prospect also appears to represent a "Noranda-type" VMS system.

The two diamond drill holes investigated at the Quartz Hill prospect comprise amygdaloidal to massive basalt/andesite lava flows, mixed volcanoclastic and chemical sediments (including chert, silicate-facies iron formation, oxide-facies iron formation), and felsic tuffs and/or tuffaceous volcanoclastic sediments. Massive to semi-massive sulfide mineralization occurs between 89 and 150 feet in exploration diamond drill hole QH-84-2, and is hosted within felsic ash tuff or tuffaceous sedimentary rocks. The relative abundance of felsic tuffs and tuffaceous material, coupled with hydrothermal alteration assemblages comprising andalusite, chloritoid, and iron-rich chlorite, suggests that the Quartz Hill mineralization may represent either a) a "Matabi-type" VMS system (Morton and Franklin, 1987); or b) an ancient shallow subaqueous or subaerial high-sulfidation system (White and Hedenquist, 1990, 1995; Sillitoe, 1995; Sillitoe et al., 1996). Matabi-type VMS systems are characteristic of shallow water (<500 meters water depth) hydrothermal systems, reflect extreme acid leaching of the rocks by the hydrothermal fluids, and may be analogous to "high sulfidation" epithermal systems within shallow water environments. Such hydrothermal systems may produce gold-rich massive sulfide deposits (Hannington et al., 1997).

The results of this study indicate that the Vermilion region of northeastern Minnesota contains at least two examples (Five Mile Lake and Eagles Nest) of deep water, flow-dominated VMS systems (Noranda-type). The Quartz Hill prospect may represent either a volcanoclastic dominated, shallow water "Matabi-type" VMS system, or a shallow subaqueous or possibly subaerial high sulfidation-type epithermal system. Continued re-evaluation of these prospects via detailed field mapping, diamond drill core relogging, petrographic analysis, and lithogeochemical studies will be performed during the next year to further evaluate and better understand these potentially ore-forming hydrothermal systems.

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MAGMATIC ORIGINS FOR NATHAN'S LAYERED SERIES: AN INITIAL REASSESSMENT OF THE MIDCONTINENT RIFT'S FIRST MAJOR PLUTONIC MATERIALS

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In recent years, great strides have been made in deciphering details of the evolution of the Midcontinent Rift System (MCR), and the emplacement of the Duluth Complex intrusions and associated lavas. The vast majority of material produced by the MCR was between 1099 and 1095 Ma (Miller and Smyk, 1995; Miller and Ripley, 1996), an indication of how vigorous the system was. The earliest materials, however, were produced in excess of 8 million years previously, and because of their relative rarity are incompletely understood.

One of the most interesting intrusions of this early period of rifting is known informally as Nathan's Layered Series after the work of Nathan (1969). His still stands as the most intensive study of the rocks, comprising field descriptions, petrographic analysis, and some microprobe and optical determinations of mineral compositions. No geochemical work has been performed on any rocks of this series. A U-Pb zircon date of $1106.9 \pm .6$ Ma has been obtained for one of the units of this series (Paces and Miller, 1993), confirming its antiquity in the MCR. Nathan (1969) identified 27 separate units, which are given the letter designations A-Z and AA in their inferred chronological order based on the discordancies observed. Nathan's own interpretation, plus those of subsequent observers, offers that many of the separate units may be gradational variations, while others may be sparse dikes or "sport" varieties, to use the terminology of Nathan (1969).

In terms of major magma bodies, the series comprises four principal units: A-B (troctolites to gabbro), G (oxide-rich olivine gabbro), M (gabbro), and P-Q (troctolites to gabbros). These units are present in amounts great enough to permit their being assigned as the principal events in the evolution of the series. Typical modal abundances and mineral compositions for these groups are given in Table 1. One of the more interesting aspects of this series is the presence of large amounts of Fe-Ti oxides in many of the units. There are several units that occasionally have in excess of 30% Fe-Ti oxides. Among the major units, only Unit G is notable for a high abundance of oxide phases, in some locations exceeding 60%. This occurs in a fairly primitive magma (forming abundant olivine of Fo₄₀₋₅₀ and little quartz or granophyre), resembling the other major magmas in other aspects.

Table 1. Typical Mineral Abundances for NLS and Model Results.

Unit	Pl	Ol	Pig	Aug	Opx	Ox	Model	Pl	Ol	Pig	Aug	Ox
A-B	42	53	3	2	---	---	6kb	47	46	2	5	---
	An ₆₁₋₆₅	Fo ₆₃	Mg _{#=69}				10%	An ₆₃	Fo ₆₂		Mg _{#=65}	
P-Q	58	3	---	32	7	---	6kb	49	14	4	33	---
	An ₅₄₋₆₀	Fo ₆₀		Mg _{#=71}			~15%	An ₆₂	Fo ₆₀		Mg _{#=68}	
M	59	---	13	24	---	2	6kb	51	6	5	34	3
	An ₅₅₋₆₃		Mg _{#=53}	Mg _{#=59}			30%	An ₅₉	Fo ₅₀		Mg _{#=58}	
G	62	5	8	11	---	14	1kb	48	6	---	28	16
	An ₅₀₋₅₅	Fo ₄₀		Mg _{#=63}			40%	An ₅₄	Fo ₄₅		Mg _{#=57}	

Petrographic data from Nathan (1969).

Modelling of magma crystallization was made to explore possible scenarios for the unusual abundance of oxide minerals in the material comprising Unit G. This modelling was done with the MAGFOX program (J. Longhi, pers. comm.). A typical composition of a Logan sill (Table 2) was used as a parent since it represents the only common composition in the region that is even remotely coeval (the Logan sills have been dated at 1108^{+4}_{-2} by Davis and Sutcliffe, 1985).

Although the constraints are poor since no liquid compositions are known for Nathan's series, some interesting features of the modelling are present. Using the Logan composition of Table 2, materials resembling those of units A-B, M, and P-Q, can be generated through crystallization at depths corresponding to 6 kb. In this, A-B and P-Q

can be formed after 10-15% crystallization, and M after ~25% crystallization. These results are shown in Table 1 adjacent to the petrographic observations of Nathan (1969). In this model, the oxide phases appear after 28% crystallization, and are moderately abundant thereafter, consistent with the few percent of oxides present in P-Q. It is interesting to note that if only one magma chamber existed at 6 kb, then the P-Q magma must be older than M, in contradiction to the original mapping. If Nathan (1969) is correct, it implies that multiple chambers existed, or that recharge was taking place, both of course plausible. At 6 kb, oxides do not form in abundances akin to those seen in Unit G until >50% crystallization, and at that point, the liquid is far more evolved than could have produced the other minerals seen. Such liquids may be responsible for the smaller intrusive dikes and sills assigned to other units by Nathan. However, lower pressures enlarge the stability field for oxide phases, and modelling at 1 kb showed ilmenite appearing after less than 20% crystallization. Materials akin to those of Unit G are suggested by the model after approximately 40% crystallization. Thus Unit G may reflect evolution in a shallower magma chamber.

The tremendous variation in cumulate textures on a small scale, and the gradational nature of the rocks is reminiscent of (and in this case may presage) the later Anorthositic Series rocks of the Duluth Complex suggested to have formed as injections of plagioclase crystal mushes (Miller and Wieblen, 1990). Thus, the rocks of Nathan's Layered Series may represent material (of Logan composition?) that was emplaced at several levels in the crust in the initial phases of rifting. Evolution in these disparate chambers would lead to some magmas having unusual amounts of oxides.

It is interesting to note that the models produced a liquid composition similar to the Grand Portage dikes (composition given by Green et al., 1987) after 35-40% crystallization at 1kb, roughly equivalent to that of Unit G. Perhaps the Grand Portage Dikes are the hypabyssal sibling of the plutonic Unit G seen further inland.

Table 2. Parent Composition Used in Modelling and one result (wt percent).

<u>Unit</u>	<u>SiO₂</u>	<u>TiO₂</u>	<u>Al₂O₃</u>	<u>FeO₂</u>	<u>MnO</u>	<u>MgO</u>	<u>CaO</u>	<u>Na₂O</u>	<u>K₂O</u>	<u>P₂O₅</u>
Logan	49.0	3.40	13.1	15.6	0.22	5.60	7.45	2.52	1.16	0.38
40% @ 1kb	53.9	2.49	13.3	15.1	0.25	2.11	7.07	2.96	1.82	0.62
Grand Portage	52.5	2.48	13.4	13.3	0.19	3.68	6.72	3.17	1.79	0.48

Logan composition from Geul (1970).

Grand Portage is an average of 17 dikes (Green et al., 1987).

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SMALL MAFIC INTRUSIONS OF THE LAKE SUPERIOR REGION: TARGETS FOR TITANIUM EXPLORATION

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Globally, high-grade magmatic ilmenite deposits are often in or closely associated with anorthosite complexes. Large layered mafic intrusions host Ti-rich magnetite in Fe-Ti oxide rocks. There are many mafic intrusions throughout the Lake Superior region that range in age from Archean to Proterozoic. However, most of these intrusions are not associated with anorthosite complexes and many are relatively small. Despite these characteristics, small mafic intrusions of the Lake Superior region have the potential to host significant amounts of Ti, based on analogy with a recently documented occurrence in Finland.

The Finnish Koivusaarenneva gabbro is a small mafic intrusion, not associated with an anorthosite complex, that contains inferred resources of 44 Mt with 15 % ilmenite and 5% V-rich magnetite (0.7 wt. % V) to a depth of 150m (an additional 44 Mt are possible to a depth of 300m). The feasibility of mining this ore body is currently being investigated by a Finnish mining company.

The Koivusaarenneva gabbro is an elongated sill-like intrusion, 0.5 to 1 km thick and 3 km long parallel to strike. The intrusion produces a 4 mGal gravity anomaly and a clear NE-SW-oriented aeromagnetic anomaly in the low-intensity background. The intrusion was emplaced at 1881 Ma into tonalitic bedrock and is part of a gabbro province interpreted to have formed in tensional zones in the vicinity of or marginal to convergent plate boundaries. The Koivusaarenneva gabbro is part of a 12 km long chain of intrusions that were emplaced along a NE-SW oriented fault zone. The intrusion is mostly composed of modally layered medium-grained and metamorphosed gabbro and gabbro-norite. The magmatic layers have been tilted to a subvertical orientation and faults segment the intrusion. The intrusion is divided into three zones on the basis of geochemistry and petrography. Fe-Ti oxide-rich layers are common in the lower and middle zones. The $\text{TiO}_2/\text{Fe}_2\text{O}_{3\text{TOT}}$ ratio is constant for all rock types in the lower zone at about 0.2. The middle zone contains the 2 km long ilmenite ore body that grades between 8 and 48% ilmenite. The $\text{TiO}_2/\text{Fe}_2\text{O}_{3\text{TOT}}$ ratio of the middle zone is between 0.25 and 0.50. The upper zone consists of P-rich gabbro and leucogabbro.

The genetic model of the intrusion and ore body begins with primary tholeiitic mafic magma emplaced in a deep magma chamber at or near the base of the crust. In the deep chamber, crystal-liquid fractionation, under conditions of very low f_{O_2} , generated Ti-enriched parent magma averaging about 3.3% TiO_2 . This parental magma was successively injected into each of the three zones of the intrusion. Variation within the lower and upper zones is consistent with closed-system crystal-liquid fractionation of two separate batches of magma from the deep chamber.

The middle zone contains the voluminous ilmenite ore. The overall composition of non-mineralized gabbro from the middle zone is compositionally similar to non-mineralized gabbro

from the lower zone, however, the weighted average composition of the middle zone is considerably higher in Ti and Fe than the weighted average composition of the lower zone. The volume of magma in the middle zone is far too small to yield the large mass of ilmenite unless the parent magma had extreme Ti and Fe. Instead, the extreme excess of Ti and Fe in the middle zone can be explained by a parent magma with elevated, but rather normal Ti and Fe (like the lower and upper zones) that flowed through the partly crystallized magma chamber. After an oxide-rich immiscible liquid was extracted from the magma this dense material sank to the floor of the shallow magma chamber to form a Fe-Ti oxide rich matrix between a silicate framework. The Ti and Fe depleted magma was then replaced by a new batch of parent magma and so on. The middle zone represents a channel for magma flow with multiple episodes required for accumulation of the large mass of oxides. A similar magma flow through model has been proposed to generate gabbro-hosted Ni-PGE sulfide mineralization at Norilsk, Russia (Naldrett et al., 1996) and Voisey's Bay, Canada (Evan-Lamswood et al., 1998).

For Ti-deposits in small mafic intrusions, an open magma flow through system is an essential genetic component to produce economic size deposits. Continuity of gabbro intrusions as a chain or along a fault zone is a favorable geologic setting. An overall elevated Ti content of non-mineralized gabbros is another favorable characteristic indicating elevated Ti in the parent magma. Small mafic intrusions of the Lake Superior region can be tested for potential to host Ti resources using an exploration model based on the Finnish Koivusaarenneva gabbro intrusion.

ADDITIONAL PALEOMAGNETIC STUDIES OF A PROTEROZOIC DIABASE DIKE, IN PIFHER AND IRWIN TOWNSHIPS, LAKE NIPIGON DISTRICT, ONTARIO

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An approximately 50 m wide porphyritic diabase dike outcrops in western Irwin and Pifher Townships in the Nipigon district and is locally known as greenspar. The dike has a characteristic greenish mottled appearance in outcrop as a result of saussaritized plagioclase glomerophenocrysts in a diabase groundmass (Luther, 1997). The dike strikes due north and dips vertically, and is found as segments, off-set by east-west faulting (Mackasey, 1975). There are no radiometric dates on this rock or associated rocks, although, it is cut by a large middle or late Proterozoic sill in Irwin Township (Mackasey, 1975).

We previously reported paleomagnetic studies on four sites from this area (Thomas and others 1998). Five additional sites were collected in the summer of 1999, primarily from locations in Pifher Township. The nine sites span approximately 27km. of the dike. Samples from each location were subjected to both alternating field (A.F.) and thermal demagnetization. The samples show one primary magnetic direction which is removed at demagnetization temperatures of 570° C. A.F. demagnetization of samples up to 60 mT, also gives only one direction of magnetization. However, the samples are quite viscous and require a long wait time in the magnetometer between measurements. All but two locations show normal polarity with northwesterly declinations (200°-300°) and inclinations of 40° to 80°. One site in southern Pifher Township appears to be reversally magnetized with declinations of 90° to 100°, and inclinations of -75°. The southern most location near Beardmore produces inconsistent results.

Overall, the magnetic directions are consistent with Keweenawan paleomagnetic directions in the Lake Superior Region.

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PETROGENESIS OF THE MIDCONTINENT RIFT GRANOPHYRIC COMPLEXES OF NORTHERN MINNESOTA

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The hypabyssal granitic rocks of northeastern Minnesota, commonly referred to as granophyres, are an important component of the Midcontinent Rift (MCR) of northeastern Minnesota. In this study we examine eight intrusive complexes associated with the rift, including detailed transects across the Misquah Hills and Greenwood Lake granophyres. Evidence from petrographic, major and trace element data suggest a combination of magma mixing, chemical differentiation, and partial melting of MCR and older crust to form the granophyre complexes.

The granophyre complexes are generally concordant intrusions that range from 30 to 150 km² in surface area and are up to 1000 meters thick. The complexes typically consist of basal diorite, monzodiorite, and quartz monzodiorite and upper granite and granodiorite. The contact zones between the mafic and felsic rocks are compositionally and structurally heterogeneous; evidence of mutual intrusive relationships between the mafic and felsic rocks can often be found within the same outcrop. Porphyritic rhyolite overlies granitic rocks of several of the complexes (e.g., Misquah Hills, Greenwood Lake, Eagle Mountain, and Lima Mountain). Thus far, only one of the complexes has been dated (Swamper Lake=Greenwood Lake granophyre, 1107 Ma $\pm$ 1.1, reversed magnetic polarity; Davis and Green, 1997); the other complexes are undated but are generally considered to have normal magnetic polarity, with the exception of the Misquah Hills body which is possibly reversed.

The mafic rocks of the complexes (e.g., quartz monzodiorite, monzodiorite, and diorite) are distinguished by abundant (15-35 vol.%) interstitial pyroxene and significant (1-3 vol.%) apatite. The felsic rocks are composed of sodic plagioclase (30-40 vol.%), orthoclase (25-35 vol.%), and quartz (20-30 vol.%). Plagioclase commonly exhibits normal and oscillatory compositional zoning; many plagioclase grains are mantled by thin rims of sodic plagioclase. Anhedral pyroxene and small Fe-Ti oxides make up less than 10% of the rock. All of the rocks in the complexes are characterized by granophyric intergrowths of alkali-

feldspar and quartz. Intergrowths are interstitial between plagioclase or more commonly radiate from euhedral plagioclase phenocrysts. Intergrown quartz ranges from coarse and micrographic cuneiforms to fine and radially granophyric shapes.

The granophyre complexes display a wide range of SiO₂ (47-76 wt %). As silica increases, TiO₂, Fe₂O₃, MnO, MgO, CaO, and P₂O₅ decrease, whereas K₂O increases. There are notable compositional "gaps" in the linear trends on Harker variation diagrams between the mafic and felsic portions of each of the complexes (Figure 1). Although rocks in the lower portions of the complexes have relatively low SiO₂ (47-62 wt.%) most are silica over-saturated and all but two samples contain normative quartz. The granitic rocks in the upper portions of the complexes are SiO₂-

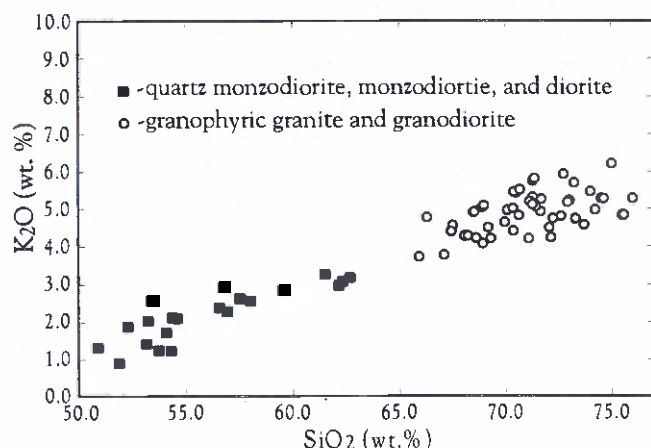


Fig. 1 - K₂O (wt. %) versus SiO₂ (wt. %) diagram for all samples from the granophyre complexes, illustrating the compositional gap between the mafic and felsic rocks of the intrusions. Note the linear trend of the major element variation with increasing SiO₂. Full data set in Kennedy (2000)

rich (66-76 wt.%), and are metaluminous to slightly peraluminous. The mafic and felsic rocks plot along linear trends on most incompatible trace element diagrams (e.g., U, Nb, Ce, and Zr vs. SiO_2); compositional "gaps" between the mafic and felsic rocks are also evident in these plots. The mafic and felsic rocks from all of the granophyre complexes exhibit negative Nb-anomalies on multi-element variation diagrams. The small variation in the Th/Nb and Ce/Nb ratios between the mafic and felsic rocks suggests that the source of the Nb depletion is common for both the mafic and felsic rocks.

Although the major element variation might be explained by crystal fractionation of a typical MCR mafic component, it seems unlikely that fractionation of mafic melts could account for the formation of this large volume of granitic rock (approximately 10-15% of the intrusive rocks of the MCR exposed in northeast Minnesota).

Furthermore, on plots of major elements versus SiO_2 (e.g., K_2O ; Figure 1) the trend of the data should change in slope as the fractionating assemblages change during crystallization. Instead, the data plot along linear trends over a wide range of SiO_2 concentrations which may indicate mechanical mixing. On diagrams of major element ratios, the mafic and felsic rocks plot along hyperbolic trends (e.g., $\text{K}_2\text{O}/\text{Fe}_2\text{O}_3^*$ vs. SiO_2/CaO , Figure 2). These trends can be modeled by mixing of a mafic (Miller & Chandler's composite Sonju Lake intrusion parental magma (1997)) and felsic (average of the most evolved samples from the granophyre complexes) end-members. If a more primitive olivine tholeiite from the NSVG is used as the mafic end member, the resulting model does not fit the data for the granophyre complexes. Samples that do not plot along this mixing line likely evolved from mixing products by fractional crystallization, which would increase SiO_2/CaO and $\text{K}_2\text{O}/\text{Fe}_2\text{O}_3^*$.

An origin for the granophyre complexes by mixing is consistent with the field relationships and linear trends on major element diagrams. However, although a combination of magma mixing and fractionation may explain the origin of the granophyre complexes, it does not explain the source of the large volume of felsic end-member necessary for mixing. Nd isotope data from the granophyre complexes suggest that the felsic component may be the result of fractionation or melting of contemporaneous crustal materials (Vervoort, this volume). Further examination is needed to determine an ultimate source for the felsic material and its relationship to the genesis of the granophyres.

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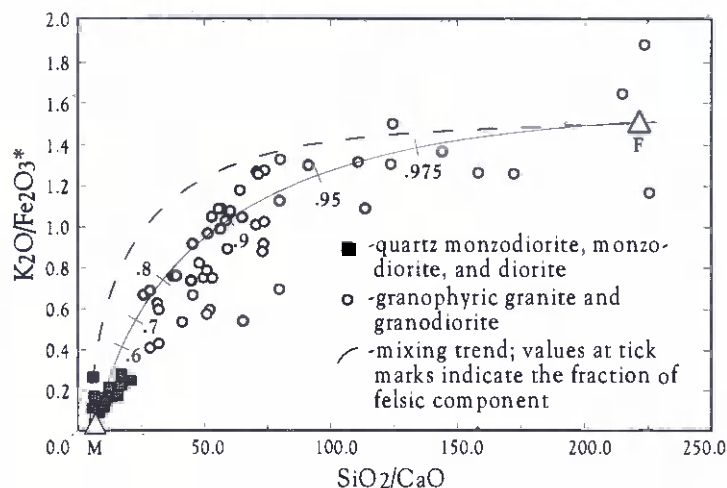


Fig. 2 - $\text{K}_2\text{O}/\text{Fe}_2\text{O}_3^*$ versus SiO_2/CaO diagram showing the hyperbolic mixing trend for all samples from the granophyre complexes, concordant with mixing model. The mixing model is based on two end member parental compositions (triangles), the Sonju Lake intrusion (M) and an average of the three most felsic granitic samples (F). The dashed line is the mixing model with the NSVG olivine tholeiite as the mafic component, which is not concordant with the data.

A POSSIBLE SUDBURY EJECTA LAYER IN THE GUNFLINT FORMATION, NORTHWESTERN ONTARIO

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Previous studies revealed that the Gunflint lapilli tuff unit, located in the Kaministiquia Gorge near Thunder Bay, Ontario, is unlikely to represent an ejecta layer from the Sudbury impact event. Euhedral zircons extracted from the lapilli tuff unit have yielded a date of 1878 ± 2 Ma (Fralick et al., 1998) presumed to be the age of sedimentation based on a volcanic source for the zircons, too old to be associated with the Sudbury event at 1836 ± 14 Ma (Krogh et al., 1984). However, a distinct ash layer approximately 100 m stratigraphically higher in section has been recently discovered and investigated.

A grey ash layer 11.5 cm thick is exposed in two locations on the southern side of the Kaministiquia Gorge. The layer is comprised mostly of friable illite and montmorillonite, but separation of particulate fractions revealed the presence of lithic fragments, mudball lapilli, crystal fragments and green spherules with a glassy appearance. The latter were found to be glauconite, which also has been described in the Gunflint lapilli tuff unit (Hassler & Simonson, 1989). The crystal fragments are mostly pure potassium feldspar, with minor quartz, calcite and various other minerals.

The glauconite pellets and potassium feldspar clasts have been interpreted as indicative of a proximal submarine volcanic vent (Hassler & Simonson, 1989). In particular, the sodium-free potassium feldspar clasts have been interpreted as the product of metasomatic replacement of igneous plagioclase. Also present are quench-textured basaltic clasts and occasional devitrified vesicular glass fragments. However, large, unstrained quartz clasts and fresh plagioclase clasts suggest that a somewhat more felsic volcanic source has also contributed to the particulate assemblage.

Analyses of samples taken at various intervals in the layer, as well as of the enclosing shales at one of the locations, revealed the presence of anomalous Ir (1.9 ppb) as well as other PGEs and Au. On the other hand, the chalcophiles Co, Cr and Ni are significantly depleted in the ash layer as compared to the enclosing shales. A strong enrichment in Zr indicates the presence of zircons, which have been separated and should again provide opportunities for dating of the material as well as investigation for shock features. Shock features in the particulate fraction have not so far been identified, and the depletion of chalcophiles is contrary to expectations in an ejecta layer (e.g. Hildebrand, 1993). However, Simonson et al. (1998) noted that the Acraman impact layer in Australia lacks this enrichment. This layer as well as a layer seen in the Hammersley Basin can be explained as the result of submarine impact. As the Sudbury Structure is believed to have formed in a marine shelf environment, the possibility of an impact origin for the Gunflint ash layer remains open. To date, however, the evidence is in favor of a volcanic source for the ash layer, but geochronology will be needed in order to exclude the possible impact origin of the layer.

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COMMINUTION AND DILUTION OF GLACIAL INDICATORS: RATE ESTIMATES FROM FIELD DATA

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Introduction: Tracing glacial indicator trains has long been recognized as being fundamentally a problem of interpreting the diminishing concentrations of an indicator with increasing transport distance from its source. The dispersal pattern of an indicator is a function of the processes of dilution and comminution acting on that indicator during transport. Numerous studies have established empirically that dispersal patterns typically take the form of an exponential decay curve. However, while an indicator ideally comprises all debris with a particular lithologic or geochemical signature derived from a unique source, in practice most indicator studies examine only a portion of the size fractions of a till.

This approach precludes precise quantification of the systematics of indicator transport, in particular quantification of dilution and comminution rates. This is due to a number of factors; previous indicator tracing studies have often been limited to examination of only a portion of the size fractions containing an indicator, and in many cases recognition of a unique indicator derived from a specific bedrock source has proven difficult. The lack of specific data relating the relative changes in indicator concentrations due to dilution (largely a function of interaction with the bed) and comminution (largely a function of the material properties of the indicator) have precluded satisfactory quantitative modeling of glacial debris transport.

The present study attempts to address these questions by examining dispersal of clasts derived from a quartz-epidote altered basalt unit in the Vermilion District, Minnesota. Bedrock within the study area consists of a metavolcanic-dominated greenstone belt striking roughly E-W. Glacial drift in the area is thin (0-10 m), and records a single advance of the Rainy Lobe, with the last glacial advance moving from the NNE. Samples were collected from basal tills, and screened to separate three adjacent size fractions (1-2, 2-4, and 4-16 mm). The quartz-epidote altered basalt indicator is visually distinct and was easily separated from each size fraction; concentrations represent mass proportions. A transport distance for each sample was calculated by measuring the distance from each sample location along the flow path to the source area.

Dispersal: The concentration of an indicator in a particular size fraction of till is a function of the change in concentration due to dilution, and the change in concentration due to comminution. The relationship between dispersal, dilution, and comminution can be expressed as:

$$C_{\text{DISP}} = C_{\text{DIL}} \cdot C_{\text{COM}} \quad (1)$$

Dispersal curves for the indicator in each particle size fraction in the study area were generated by plotting indicator concentration against transport distance (T, in km) (Fig. 1). Concentrations of the largest clasts (4-16 mm) decreased with transport distance at the fastest rate, while medium-sized (2-4 mm) clast concentrations decreased at a lower rate. Dispersal of the smallest clasts (1-2 mm) has a curious form; concentrations increase during the first ~5 km of transport, then decrease with increasing transport distance.

Dilution: Dilution reduces indicator concentration by eroding and incorporating material from the bed downflow from the indicator source. A dilution curve should ideally take the form of a power function, with the exact slope of the dilution curve at any given point in space and time a function of distance from the source and the instantaneous rate of erosion and entrainment. These are dependent on a number of variables, including bed roughness, bed composition, and the basal thermal regime. Deviations of a

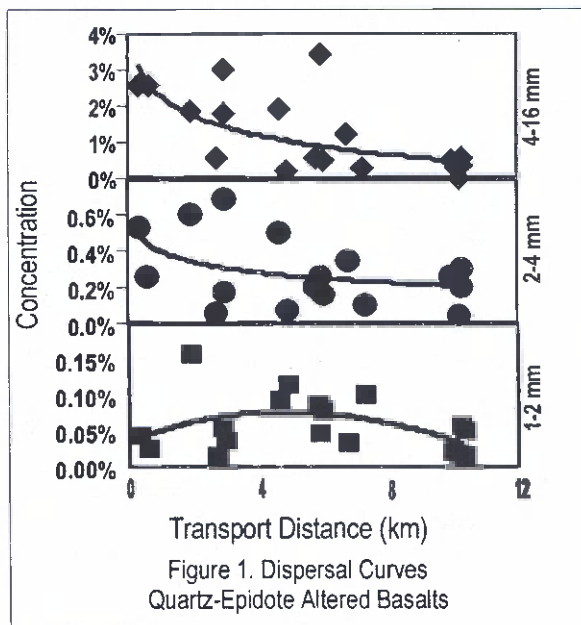


Figure 1. Dispersal Curves
Quartz-Epidote Altered Basalts

dilution curve from a power function of represent deviations from uniform conditions. However, over relatively short distances on a bed of uniform composition it is reasonable to assume a uniform rate of erosion and incorporation.

An estimate of the dilution rate in the Vermilion District was obtained by calculating the total proportion of indicator material in the 1-16 mm fraction of the total sample (Fig. 1). Regression analysis of these data results in the following equation for dilution:

$$C_{DIL} = 0.0348e^{-0.0002T} \quad (2)$$

Clearly, this dilution rate represents non-ideal conditions. This is dominantly an artifact of not including the <1 mm and >16 mm size fractions in the calculations, however it represents a reasonable estimate.

Comminution: Comminution alters the concentration of an indicator within a particular size fraction as particles are broken down by clast-on-clast and clast-on-bed interactions. Larger clasts tend to comminute more rapidly than smaller clasts. Larger clasts are not lost to the system as they break down, but are transferred to smaller size classes. The concentration of an indicator in a particular size fraction at a given transport distance is thus a function of the rate at which particles are being added to the size class by comminution of larger clasts, and the rate at which particles are leaving the size class by comminution to smaller clasts.

Comminution rates for indicator clasts in the Vermilion District were calculated by rearranging equation (1) and solving for C_{COM} at each sample location using the model C_{DIL} (Fig. 3). C_{COM} for the largest particles showed poor correlation with transport distance; this is probably a result of significant variation in indicator boulder concentrations along individual flow lines resulting from variable rates of addition by boulder comminution to this size class. Medium-sized particles showed a relatively sharp increase in C_{COM} with transport distance, reflecting the higher rate of comminution of the coarsest particles. The smallest particles showed a lower rate of increase reflecting the lower rate at which coarser particles are comminuted to this size class.

Conclusions: Results of indicator tracing in the Vermilion District illustrate the importance of segregating the effects of dilution and comminution to modeling the concentration of an indicator at a particular transport distance. Dilution affects the concentration of each particle size equally, however comminution rates strongly and differentially influence indicator concentrations in differing size classes. Since clast comminution is controlled by grain size and material properties, the concentration of an indicator at a particular transport distance can be seen to be dominantly a function of the initial particle size distribution and the material properties of the indicator.

This study focused on dispersal of quartz-epidote altered basalts. However, several other dispersal trains were recognized in the Vermilion District during the course of the study, including ankerite-sericite lode gold-associated alteration, and iron formation, each displaying a unique dispersal pattern. Given an identical glacial environment, these differences must be a reflection of the differing material properties of the indicator. These data underscore the potential problems that may accompany application of a general regional dispersal model to interpreting particular localized glacial indicator trains.

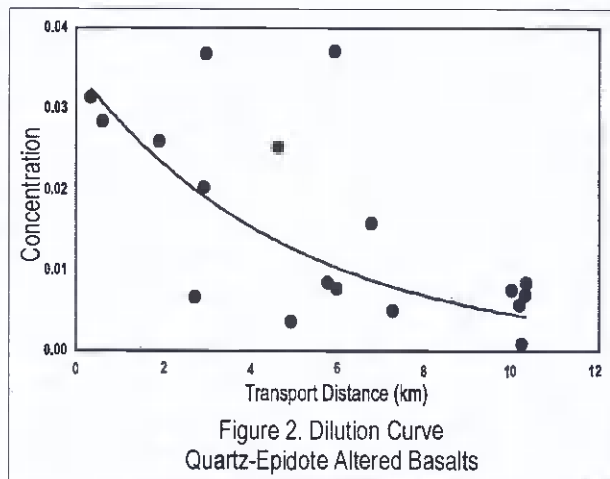


Figure 2. Dilution Curve
Quartz-Epidote Altered Basalts

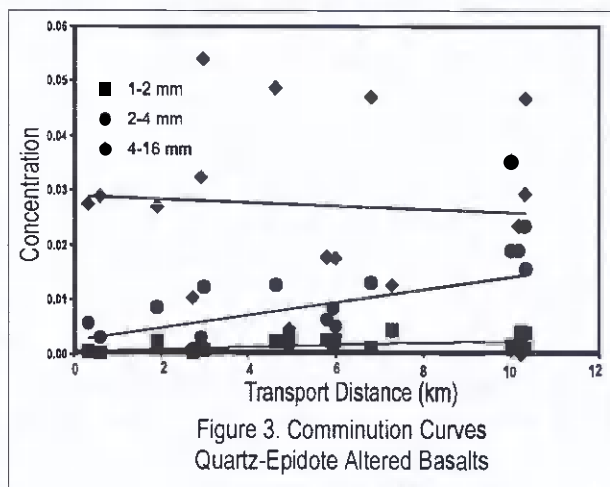


Figure 3. Comminution Curves
Quartz-Epidote Altered Basalts

Low-grade metamorphism of an Archean debris flow,
Irwin, Pifher, and Meader Townships, Lake Nipigon Region, Ontario

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This extensive body of volcanic breccia is located east of Lake Nipigon in northern Irwin, southeastern Meader, and a large part of southern and eastern Pifher Townships. It is 10-25 km east of Lake Nipigon and 17-28 km north-northeast of Beardmore. Mapping by Mackasey (1975), Kresz and Zayachivsky (1989), and as a part of this study shows this rock to be enclosed in a thick sequence of typical greenstone assemblage rocks. Metamorphism, probably caused by large granitic intrusives in Pifher Twp, increases to the northeast.

The breccia was thoroughly described and an origin as a subaqueous debris flow was documented by Luther (1998). In brief, the breccia consists of rounded rock fragments ranging from <1 mm to over 1 m in a very fine-grained matrix. Larger fragments tend to be similar to the matrix in composition while smaller fragments vary in composition from that of the matrix to mafic to ultramafic to carbonate-rich. The matrix of the breccia was composed of quartz grains, euhedral and broken crystals of plagioclase, a glass shard/pelitic fraction (now replaced by the greenschist metamorphic assemblage described below), and pyroxene and/or hornblende (now chlorite) up to 0.5 mm. Representative whole rock analyses of the portion of the breccia affected by low-grade metamorphism are presented in Table 1; these analyses show the average (igneous rock equivalent) composition of the breccia to be dacitic.

A metamorphic assemblage of Mg-Fe chlorite, high-Al to high-Fe epidote, aluminous actinolite, phengitic-paragonitic sericite, albite, high-Fe biotite, and minor K feldspar over-prints the primary texture and replaces the glass/pelitic fraction; EMPA analyses of the more voluminous metamorphic-origin minerals are given in Table 2. Most of the metamorphic minerals, as is to be expected in greenschist facies rocks, show minor variation in individual mineral compositions; two minerals, plagioclase and epidote, show major compositional variation. Plagioclase is present in two varieties: $\sim \text{an}_5$ and $\sim \text{an}_{40}$. The large plagioclase crystals have a composition of $\sim \text{an}_{40}$ and are partially saussuritized; these grains are interpreted as relict igneous plagioclase. The small matrix grains of plagioclase are $\sim \text{an}_5$; these grains are interpreted as metamorphic plagioclase generated by recrystallization of the breccia matrix. The variation in epidote composition probably represents crystallization of epidote over a range of temperatures; high-Al epidote usually crystallizes at a higher temperature than the high-Fe epidote.

In summary: a classic greenschist facies mineralogy of albite, epidote, muscovite, biotite, actinolite, and chlorite overprints the primary mineralogy of the debris flow which included finely-crystalline quartz, glass and altered glass (pelite), and detrital quartz, plagioclase, and mafic minerals grains.

Table 1. Whole rock analyses of the samples of the volcanic breccia which were affected by low-grade metamorphism. Analyses by XRAL.

	<u>SIO2</u>	<u>AL2O3</u>	<u>CAO</u>	<u>MGO</u>	<u>NA2O</u>	<u>K2O</u>	<u>FE2O3</u>	<u>FEO</u>	<u>MNO</u>	<u>TIO2</u>	<u>P2O5</u>	<u>LOI</u>	<u>SUM</u>
<u>LN97-3-1A</u>	61.0	16.0	3.84	4.00	3.40	1.72	6.25	4.30	0.08	0.58	0.15	3.20	100.3
<u>LN97-6-1B</u>	63.2	16.5	6.03	2.15	3.53	1.49	5.30	3.10	0.07	0.51	0.11	0.85	99.8

Table 2. Chemical analyses of major greenschist-facies minerals in the volcanic breccia. Analyses by electron microprobe at UW-Madison.

	<u>actinolite</u>	<u>lo-Al epidote</u>	<u>hi-Al epidote</u>	<u>biotite</u>	<u>chlorite</u>
SiO2	55.5	37.0	37.9	35.2	25.3
TiO2	0.0	----	0.3	1.7	0.1
Al2O3	5.1	23.9	28.0	16.8	20.9
FeO	10.6	10.9	5.6	20.2	23.2
MnO	0.2	0.2	----	0.2	0.3
MgO	13.4	----	0.1	10.3	16.3
CaO	11.3	23.1	24.3	----	0.1
Na2O	1.6	----	----	0.1	0.4
K2O	<u>0.2</u>	<u>----</u>	<u>----</u>	<u>9.9</u>	<u>0.1</u>
TOTAL	97.9	95.1	96.2	94.4	86.7

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THE BARRON SAPROLITE: CONFIRMATION OF MATURE CHEMICAL WEATHERING IN THE SOURCE FOR PALEOPROTEROZOIC QUARTZ ARENITES IN THE LAKE SUPERIOR REGION

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It has long been inferred that the post-1760 Ma supermature Baraboo, Sioux, Barron and related quartz arenites were derived from sources that experienced mature chemical weathering, due to the near absence of feldspar in the arenites and predominance of kaolinite and pyrophyllite in the argillaceous strata (Dott, 1983; Ojakangas and Weber, 1984; Southwick et al., 1986). Paleosols have been recognized beneath the Baraboo, Sioux, and Barron quartzites (Medaris et al., 1997; Southwick and Mosler, 1984), and the present report is part of a continuing investigation to determine the chemical maturity of such paleosols and to evaluate the climatic conditions associated with genesis and deposition of the supermature sedimentary rocks.

A large outcrop of red saprolite occurs beneath the Barron Quartzite on the south bank of Weirgor Creek, ~100m east of Reichel Road, in Rusk County (NW1/4, SW1/4, Sec 9, T36N, R7W). The closest basement exposure is ~½ mile south, where metatonalite crops out on both sides of Reichel Road. Although the saprolite and metatonalite outcrops are ½ mile apart, the close similarity in their textures (Fig. 1) makes the metatonalite a reasonable protolith candidate. The metatonalite has inequigranular texture, in which large quartz grains are surrounded by a medium- to fine-grained granoblastic assemblage of quartz, plagioclase, hornblende, epidote, and opaques. The texture of the metatonalite has been preserved in saprolite, in which large relict quartz grains are surrounded by a matrix of finer-grained quartz, kaolinite-rich domains (after feldspar), hematite-rich domains (after hornblende), traces of sericite and tiny, euhedral crystals of crandallite-florencite (aluminophosphate minerals).

The most striking feature of the saprolite chemical composition is the virtual absence of MnO, MgO, CaO and Na₂O and the low concentration of K₂O (Table 1). The chemical index of alteration (CIA) for the saprolite is 95.7, illustrating the high degree of maturity attained by chemical weathering of the saprolite [CIA = 100*Al₂O₃/(Al₂O₃+CaO+Na₂O+K₂O) on a molar basis]. The isocon method (Grant, 1986) has been used to evaluate the magnitude of chemical changes associated with weathering, taking metatonalite as protolith for the saprolite. When oxides and elements in saprolite and protolith are plotted against each other (Fig. 2), Al₂O₃, TiO₂ and Zr lie on a straight line, an isocon, along which the relative concentrations of the defining constituents remained constant during

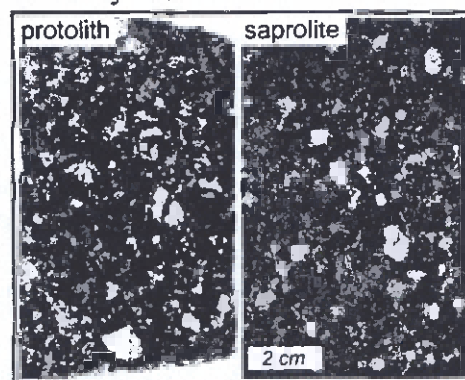


Figure 1. Polished slabs of Barron metatonalite protolith and saprolite; light grains are quartz.

Table 1. Chemical Analyses

wt %	(1)	(2)	(3)
SiO ₂	67.85	70.25	-10
TiO ₂	0.24	0.29	0
Al ₂ O ₃	14.00	16.15	0
Fe ₂ O ₃	5.63	7.05	+9
MnO	0.07	0.00	-100
MgO	2.41	0.09	-97
CaO	4.08	0.04	-99
Na ₂ O	3.68	0.01	-100
K ₂ O	1.17	0.58	-57
P ₂ O ₅	0.06	0.05	-35
LOI	0.70	5.53	
Sum	99.91	100.06	
ppm			
Rb	14	8	-52
Sr	321	90	-76
Ba	251	31	-89
Zr	80	91	0

(1) Barron metatonalite protolith
(2) Barron saprolite
(3) % change relative to isocon

weathering. The relatively small deviation of Fe_2O_3 from the isocon may be due to an unrepresentative concentration of Fe_2O_3 in the assumed protolith, rather than its mobility. The isocon slope of 1.15 corresponds to a 13% mass decrease during weathering, when MnO , MgO , CaO and Na_2O were effectively completely removed, and K_2O , P_2O_5 , Rb , Sr and Ba were substantially removed from metatonalite (Table 1).

The Baraboo Quartzite is also underlain by a saprolite on Baxter Hollow granite (Medaris et al., 1997), and application of the isocon technique to the Baraboo saprolite yields an isocon defined by Al_2O_3 and TiO_2 with a slope of 1.14, corresponding to a 12% mass decrease, similar to that for the Barron saprolite. Chemical maturity of Baraboo saprolite is comparable to that of Barron saprolite, as indicated by the levels of depletion in MnO , MgO , CaO , Na_2O , Sr and Ba (Fig. 3). Depletion of SiO_2 is ~10% in both saprolites, and ~30% Fe_2O_3 was removed at Baraboo. Following weathering of the Baraboo saprolite, K_2O and Rb were reintroduced by hydrothermal fluids, which were channeled along the sub-Baraboo unconformity during metamorphism.

The Barron and other contemporaneous saprolites exhibit a high degree of mineralogical and chemical maturity, similar to that found in present-day weathering zones in humid, warm climates, where intense chemical leaching is characteristic, thereby demonstrating the existence of a tropical environment in the Lake Superior region at ~1750-1650 Ma. Such a climate, combined with a stable tectonic setting, was essential for generating the supermature features of the Baraboo, Barron and Sioux quartzites.

Acknowledgments I'm indebted to Mike Mudrey, who drew my attention to the Barron saprolite and provided a locality map, and to Jim Grant, who enlightened me regarding the isocon method.

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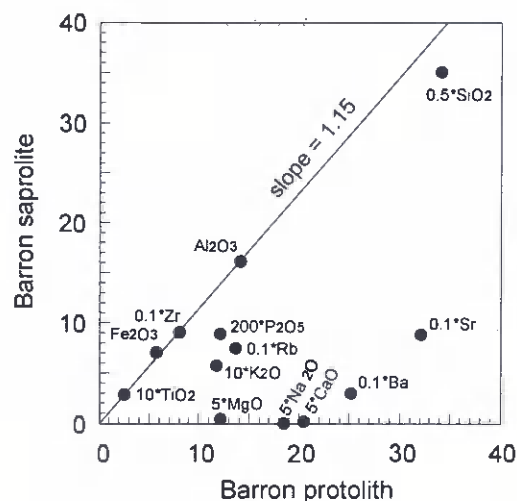


Figure 2. Isocon diagram for Barron protolith and saprolite; oxides in wt%, elements in ppm.

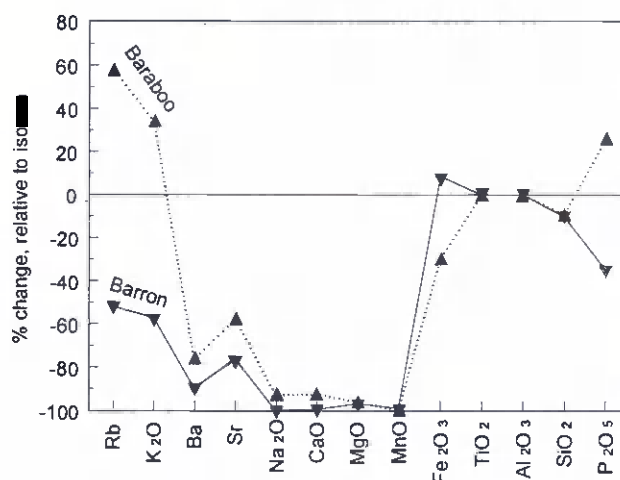


Figure 3. Comparison of chemical changes in Barron and Baraboo saprolites; elements and oxides arranged in order of decreasing ionic radius.

TOURMALINE-BEARING QUARTZ VEINS IN THE BARABOO QUARTZITE: A NEW OCCURRENCE OF THE ALKALI-DEFICIENT TOURMALINE, FOITITE

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Tourmaline has long been known to occur in quartz veins in the Baraboo Quartzite, but its chemical composition and geological significance have never been assessed. The present investigation was undertaken to characterize this tourmaline, as part of an ongoing project to establish the mineralogical and chemical composition of Proterozoic rocks in the Baraboo Range.

Three samples of tourmaline-bearing quartz veins from low in the Baraboo stratigraphic section on the south limb of the Baraboo syncline were selected for investigation: *sample 1*) a folded, 1.5 cm thick quartz vein in the regolith of the Baraboo paleosol from drill core 613 in Baxter Hollow; *sample 2*) a 3 cm thick quartz vein in quartzite in the SE ¼ Sec. 29, Baxter Hollow; and *sample 3*) a 3 mm thick, tourmaline-rich quartz vein in quartzite and metapelite in the NW ¼ Sec. 35, Pine Hollow. All three samples are mineralogically simple, consisting of quartz, specular hematite and tourmaline.

Tourmaline occurs in clusters of small, randomly oriented pleochroic crystals (Fig. 1), in which O = pale to medium grayish blue and E = colorless.

Tourmaline analyses were obtained by wavelength dispersive spectrometry on a Cameca SX50 instrument, using a 15 kV accelerating voltage, a 10 nA beam current, a beam diameter of 1 µm, the $\phi\rho Z$ reduction software, and a combination of natural and synthetic minerals as standards. Analysis of tourmaline by electron microprobe presents a challenge because of the inability to measure Li and H directly, the difficulty in determining B and O precisely, and the uncertainty in valency of transition elements. Nevertheless, acceptable results are achieved by normalizing cations to 24.5 oxygens on an H₂O- and B₂O₃-free basis and assuming a stoichiometric formula containing 3 B atoms and 31 O atoms (in the absence of F). Tourmaline was analyzed for Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K, F, and Cl, but only Si, Al, Fe, Mg, and Na were detected (Table 1). The Baraboo samples are Fe-rich, the Y-site is effectively filled with Fe and Al (means and standard deviations are 2.96±0.05, 2.96±0.08 and 2.98±0.06 for the three samples), indicating the absence of Li, and the X-site is largely vacant, containing subordinate amounts of Na.

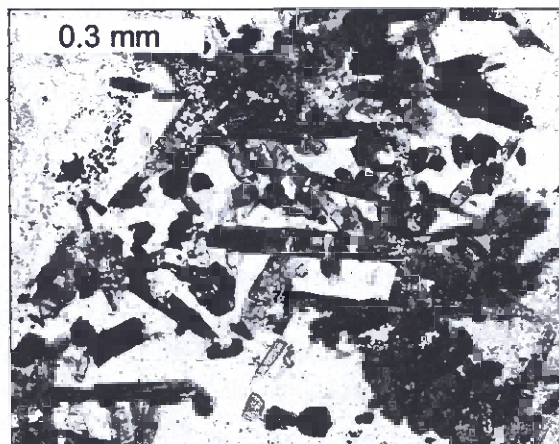


Figure 1. Photomicrograph of tourmaline, sample 3, plane polarized light

Table 1. Electron microprobe analyses of tourmaline from quartz veins in Baraboo Quartzite

sample	1	2	3
wt%			
SiO ₂	35.14	35.23	35.18
Al ₂ O ₃	34.00	35.05	34.86
FeO	13.98	12.35	14.59
MgO	0.49	1.11	0.00
Na ₂ O	0.62	0.55	0.47
Sum	84.23	84.29	85.09
cations p.f.u.			
Si	6.00	5.96	5.96
Al	6.85	6.98	6.96
Fe	2.00	1.75	2.07
Mg	0.12	0.28	0.00
Na	0.20	0.18	0.15
site occupancy			
T(6)	6.00	5.96	5.96
Z(6)	6.00	6.00	6.00
Y(3)	2.97	3.01	3.03
X(0-1)	0.20	0.18	0.15

Thus, the composition of Baraboo tourmaline is close to type foitite and lies in a field near the foitite corner of a plane defined by the tourmaline end-members, foitite $[\square(\text{Fe}^{2+}_2\text{Al})\text{Al}_6\text{Si}_6\text{O}_{18}(\text{BO}_3)_3(\text{OH})_3(\text{OH})]$, schorl $[\text{Na}(\text{Fe}^{2+}_3)\text{Al}_6\text{Si}_6\text{O}_{18}(\text{BO}_3)_3(\text{OH})_3(\text{OH})]$, and their Mg counterparts (Fig. 2).

All three Baraboo samples are alkali-deficient, with $0.5 < X_{\square} < 0.9$, although they each occupy a different field in Fig. 2. The Fe # in sample 3 is 99-100 and in sample 2 is 90-95, but sample 2 is more magnesian, with the Fe# of rims being 70-85 and of cores, 35-55. The effective operation of the coupled exchange, $X(\square) + Y(\text{Al}) = X(\text{Na}) + Y(\text{Fe}+\text{Mg})$, is illustrated by the linear covariance of Al and Fe+Mg (Fig. 3).

Most analyses extend from the theoretical composition of foitite (7 Al, 2 Fe+Mg) toward that for schorl (6 Al, 3 Fe+Mg), although the cores of tourmaline in sample 3 are more aluminous, extending toward 8 Al and 1 Fe+Mg, which, in the absence of F and Li, suggests the presence of an oxy-foitite component $[\square(\text{Fe}^{2+}\text{Al}_2)\text{Al}_6\text{Si}_6\text{O}_{18}(\text{BO}_3)_3(\text{OH})_3\text{O}]$.

Foitite is a relatively uncommon variety of tourmaline that has been described from late-stage hydrothermal veins associated with granitic pegmatites and from metasomatized wall rocks in areas of Pb-Zn mineralization. Such foitite differs from that at Baraboo in containing appreciable quantities of Ti, Mn, Ca, Li and F, depending on locality, and in being associated with a variety of silicate minerals, including albite, adularia, micas and zeolites, among others. In contrast, the Baraboo foitite is chemically simple, containing only Si, Al, Fe, Mg and Na (+ B+O+H), and is accompanied solely by quartz and hematite. The chemical constitution and alkali deficiency of Baraboo tourmaline are consistent with its environment of formation in hydrothermal veins within Baraboo metasedimentary rocks. During post-Penokean folding and low-grade metamorphism, hydrothermal fluids migrated through the chemically mature Baraboo sequence, which consists almost entirely of SiO_2 , Al_2O_3 and Fe_2O_3 , where they scavenged B and the few other elements necessary to precipitate quartz, hematite, and alkali-deficient tourmaline. Thus, the chemical and mineralogical compositions of hydrothermal quartz veins in the Baraboo range are inherited in part from Proterozoic weathering and sedimentation processes.

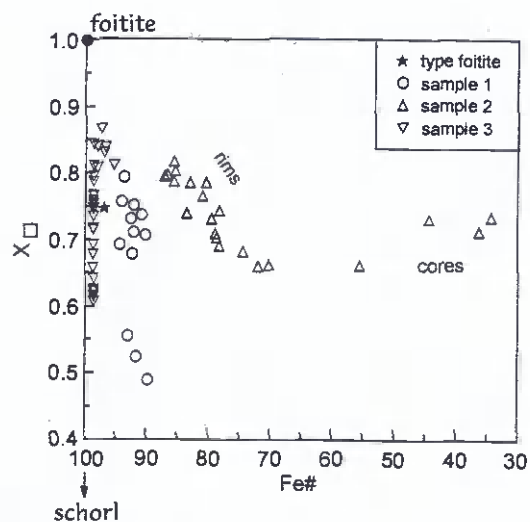


Figure 2. Compositional variation of Baraboo tourmaline in terms of X-site vacancy, $\square$, and Fe#, $100 \cdot \text{Fe}/(\text{Fe}+\text{Mg})$

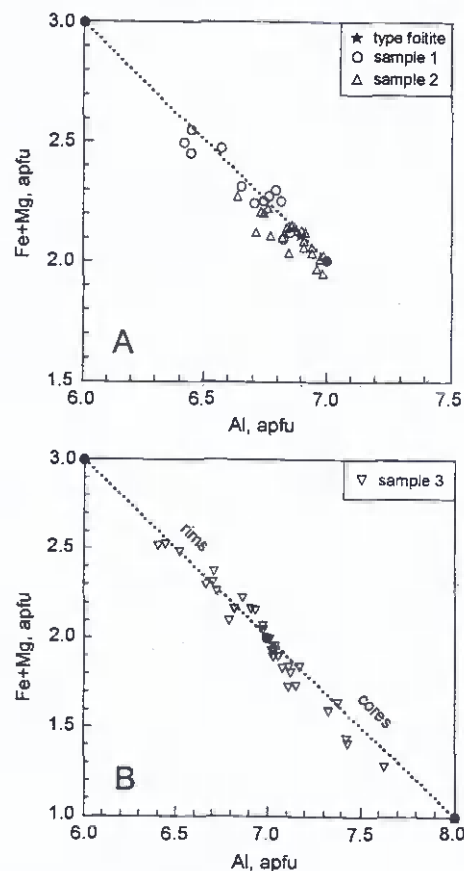


Figure 3. Covariance of Fe+Mg (Y-site) and Al (Y- and Z-sites) in Baraboo tourmaline; scale in atoms per formula unit

**Kimberlite, Base Metal, Gold and Carbonatite Exploration Targets,
Derived From Overburden Heavy Mineral Data, Killala Lake Area,
Northwestern Ontario.**

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ABSTRACT

Since 1993, the Ontario Geological Survey (OGS) has conducted a series of Quaternary mapping and overburden sampling programs to assess the diamond potential of the Kapuskasing Structural Zone (KSZ). Kimberlite is recognized as the primary host rock for diamond. A suite of heavy minerals (Cr-pyropes garnet, chromite, Mg-rich ilmenite, Cr-diopside and forsteritic olivine) are commonly associated with kimberlite and are referred to as kimberlite indicator minerals (KIMs). The types and distribution of KIMs recovered from these programs clearly demonstrate that the KSZ has excellent potential for hosting diamond-bearing kimberlite. To date, 2 occurrences of diamond-bearing rock and kimberlite have been discovered in the Wawa area (KWG Resources Inc./Spider Resources Inc., Press Release, 20/08/97; Canabrava Diamond Corporation, Press Release, 09/12/97; Band-Ore Resources Ltd., Press Release 10/02/00; Pele Mountain Resources Inc., Press Release, 10/02/00).

Following the success of the KSZ Quaternary mapping and overburden sampling programs, plans to assess similar structures in other parts of Ontario were made. One such area, the Trans-Superior Tectonic Zone (TSTZ), extends from Michigan north-northeast into Ontario, west of Marathon. Kimberlites straddle the structure within Michigan and ultramafic lamprophyres, which may belong to the kimberlite "clan", are recognized in association with the TSTZ in Ontario. The TSTZ represents a fault system that has accommodated emplacement of upper mantle derived material. To evaluate the kimberlite potential of the TSTZ in Ontario, an area between the towns of Marathon and Terrace Bay was chosen for Quaternary mapping and stream sediment and till sampling. Collected overburden samples were processed to determine KIM signatures.

In addition to KIMs, overburden samples were processed for metamorphic or magmatic massive sulphide indicator minerals (MMSIM), gold grains and carbonatite indicator minerals. The MMSIMs are associated with 3 main types of base metal deposits: 1) volcanosedimentary massive sulphides in high grade regional metamorphic terrain; 2) skarn and greisen deposits; and 3) magmatic Ni-Cu sulphides. The composition of gahnite, a rare and important MMSIM associated with metamorphosed volcanosedimentary massive sulphide deposits, can also be used to indicate the presence of rare-element pegmatite. The presence and distribution of MMSIMs and gold grains recovered from overburden sampling programs completed over the KSZ defined several important base metal, rare-element pegmatite and gold exploration targets.

This presentation provides data and preliminary interpretations on the types and distribution of kimberlite heavy mineral indicators (KIMs), metamorphic or magmatic massive sulphide indicator minerals (MMSIMs), gold grains and carbonatite indicator minerals from modern

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alluvium and till samples collected in the Killala Lake area, northwestern Ontario. This data can be used to focus exploration efforts for kimberlite (diamonds), base metal, gold and carbonatite (rare earth) deposits. A total of 230 modern alluvium and 82 till samples were collected from across the study area.

In addition to the modern alluvium and till samples, 8 bedrock samples were collected and processed to characterize their heavy mineral composition. Orientation surveys were completed over the Prairie Lake Carbonatite, Major General Resources Ltd.'s Spider Lake base metal deposit and Cameco Gold Inc.'s Empress Hill gold deposit. These surveys defined overburden heavy mineral signatures associated with each deposit type. Bedrock and overburden data obtained from the orientation surveys were used to help interpret heavy mineral signatures derived from the regional overburden sampling program.

From the overburden samples, a number of kimberlite indicator minerals, base metal indicator minerals, carbonatite indicator minerals and a few gold grains were recovered. This data will be released in an Ontario Geological Survey Open File Report, number 6013, April 2000.

Nature and distribution of Logan diabase sills and gabbro channels in the Keweenawan Rift near Thunder Bay, Ontario: Brief comparison to Noril'sk

Jon North - North Atlantic Nickel Corp.

Flat-lying Logan diabase sills, vertical diabase dikes, and layered gabbro complexes intrude lower Proterozoic and Archean rocks in the northwest corner of the Keweenawan Rift. These 1108 Ma plutonic and hypabyssal rocks are broadly contemporaneous with thick sequences of flood basalt of the North Shore Volcanic Group and Osler Group in northern Lake Superior and they ostensibly represent the magma pathways for the flood basalts. South of Thunder Bay, a rugged, upland area of diabase-capped cuestas occupies a 70 km by 30 km northeast-trending topographic feature - the "Logan Basin" - between Thunder Bay and the Minnesota border. The Keweenawan diabase caps of the cuestas (i.e. the Logan Sills) commonly rise 150 m above valleys and canyons underlain by deeply eroded flat-lying sedimentary rocks of the lower Proterozoic Rove Formation of the Animikie Group. Northwest of the Logan Basin Archean granitoid rocks of the southern Superior Province form low rolling hills. Southeast of the Logan Basin the topography is a rugged upland area of northeast-trending, linear ridges formed by vertical diabase and gabbro dikes intruded discordantly through the flat-lying stratigraphy of the Animikie Group. Geological maps of the area (e.g. Smith and Sutcliffe 1987; 1989, Pye and Fenwick 1963) tentatively illustrate NE-trending faults on the NW and SE sides of the Logan Basin.

The Logan Basin has relatively high total magnetic intensity (TMI), high magnetic relief, and long wavelength magnetic anomalies caused by the flat-lying, magnetic diabase-capped cuestas. North of the Logan Basin a domain of low TMI and low relief coincides with Archean crust and southeast of the Logan Basin high TMI, high relief, and high frequency magnetic anomalies coincide with the area of northeast-trending diabase dikes. Northeast and east-trending faults can be interpreted as the boundaries of the Logan Basin.

The juxtaposition of the domain of sills of the Logan Basin against the domain of dikes to the southeast can be reconciled in an hypothetical cross section if the Logan Basin is interpreted as a graben where the transition from vertical dikes to horizontal sills is preserved at depth. The northeast-trending dikes to the southeast are vertical conduits to the Logan sills unroofed by erosion in a horst-like feature.

In 1995 a local prospector drilled a 499 m vertical hole into the Logan Basin in Blake Township and discovered an unusual, 131 m-thick sulphide-bearing gabbro below the Logan Sills. Lightfoot and Lavigne (1995) compared the geology and texture of the gabbro to the fertile Ni-Cu-PGE bearing sub-horizontal gabbro channels below the flood basalt sequence at Noril'sk, Siberia, the world's largest nickel deposit.

North Atlantic Nickel subsequently determined that the gabbro was a flat-lying, northeast-trending, taxitic-textured intrusion up to 130 m thick which pinches down to a normal-looking Logan diabase sill less than 20 m thick within 300 m of the centre of the intrusion. An interpretation is that the transition from vertical dikes to horizontal sills in the Logan Basin is accompanied by horizontal magma channelling. This discovery underscores the potential for Noril'sk-type Ni-Cu-PGE concentrations in the basal part of the flood basalt sequence of the Keweenawan Rift - an idea that has been developed and advanced by several workers in the past decade.

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GEOMETRY BETWEEN GOLD-RICH SUBSIDIARY SHEAR ZONES AND MAJOR STRUCTURES: IMPLICATIONS FOR ARCHEAN LODE-GOLD MINERAL EXPLORATION

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Detailed GIS-based spatial analysis of the three largest Archean lode-gold mining camps in Canada has led to the development of some seemingly fundamental geometric relationships between major structures, subsidiary structures, and gold mineralization. The lode-gold mining camps included in the analysis are the Timmins, Kirkland Lake – Larder Lake, and Hemlo districts, which together have produced approximately 115 million ounces of gold. Additional analysis of the Noranda, Cadillac, and Malaretic gold camps of northwestern Quebec corroborate the original findings, and add strength to the implications of the model. The relationships link the location and size of gold mines with the sense of shear, stress regime (compression versus extension versus parallel), and distance to the major structures in each camp. Additional analysis documents the relationship between the location and size of gold mines to the orientation and distance to subsidiary shear zones in the camps. These relationships allow the exploration geologist to quickly develop specific lode-gold structural targets based on the simple analysis of geologic maps.

For this study, the major shear zones were divided into compressional, extensional, and shear parallel segments based on regional geological maps and literature review (see inset map of Figure 1). GIS analysis has shown that essentially all of the gold in the camps has been mined within 6 kilometers of major shear zones (Table 1a). In addition, greater than 98% of the gold in the three camps has been mined from zones of regional compression (Table 1b). Together, these facts lead to the conclusion that lode-gold mineral exploration programs should be targeted upon areas within 6 kilometers of compressional zones of major shear zones.

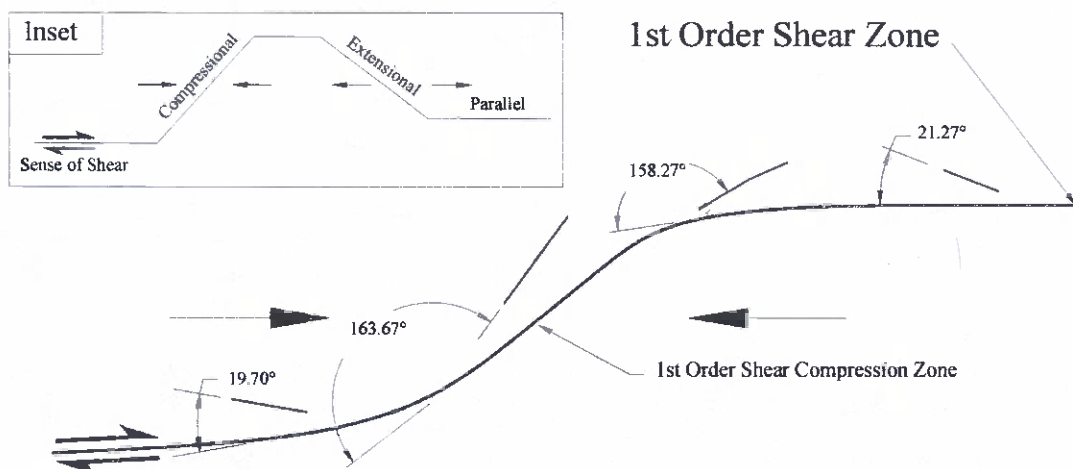


Figure 1 Regional shear zone classification (inset map) and rules for classifying the geometry of subsidiary shear zones spatially associated with major structures. Angles are measured along arcs from inferred intersection points, in the same direction as the major structures sense of shear.

Table 1 Proximity (A) and structural (B) relationships between lode-gold mines and major structures for the Timmins, Kirkland Lake-Larder Lake, and Hemlo gold camps, Ontario.

<i>A) Proximity Analysis</i>			<i>B) Structural Analysis</i>		
<i>Distance to Major Structure</i>	<i>Mined Gold (million Oz)</i>	<i>(%) Gold</i>	<i>Structural Setting</i>	<i>Mined Gold (million Oz)</i>	<i>(%) Gold</i>
< 3 Kilometers	83.108	72.0%	Compressional	113.539	98.35%
3 – 6 Kilometers	32.100	27.8%	Extensional	1.877	1.63%
> 6 Kilometers	0.235	0.2%	Parallel	0.027	0.02%

Table 2
Proximity (A) and structural (B) relationships between lode-gold mines and subsidiary structures for the Timmins, Kirkland Lake-Larder Lake, and Hemlo gold camps

<i>A) Proximity Analysis</i>		
<i>Distance to Subsidiary Shear</i>	<i>Mined Gold (million Oz)</i>	<i>(%) Gold</i>
< 200 meters	108.417	93.91%
200 – 250 meters	5.869	5.08%
250 – 300 meters	0.510	0.44%
> 300 meters	1.157	1.00%
<i>B) Structural Analysis (250 m Buffer)</i>		
<i>Subsidiary Shear Angle</i>	<i>Mined Gold (million Oz)</i>	<i>(%) Gold</i>
160° - 180°	106.252	92.97%
140° - 160°	1.398	1.22%
120° - 140°	0.000	0.00%
100° - 120°	0.400	0.35%
80° - 100°	0.000	0.00%
60° - 80°	1.200	1.05%
40° - 60°	0.006	0.01%
20° - 40°	0.860	0.75%
0° - 20°	4.170	3.65%

For this study, the relationship between the major and subsidiary structures has been defined by measurements along an arc in the same direction as the dominant sense of shear of the major structure (Figure 1). Each subsidiary shear zone segment has an associated angle to the major structure stored in its associated GIS database. The location of gold mines and their production records in each camp were spatially linked with the nearest subsidiary shear zone. The outcome of this spatial analysis is given in Table 2. Approximately 99% of the gold in the camps has been mined within 250 meters of a subsidiary shear zone (Table 2a). In addition, subsidiary high-angle (160°-180°, Figure 1) structures in the compressional zones of the major structures account for ~93% of all gold mined in the camps (Table 2b).

Area calculations in Table 3 display the usefulness of this analysis for gold exploration. Programs that would be targeted upon the high-angle (160°-180°) subsidiary in regional compressional zones would reduce the total area to be explored by ~ 99%. Similar targeting criteria in lode-gold exploration programs would greatly lower cost, reduce time, and would quickly vector the program into areas of high lode-gold mineral potential.

Table 3 Tabulation of the total GIS map area, areas within 250 meters of high-angle subsidiary shears, and percentage of the map area reduced if exploration would be targeted only in the most favorable areas of the three mining camps.

<i>Mining Camp</i>	<i>GIS Map Area (Km²)</i>	<i>Area (Km²) of 250m Buffer Around Hi-angle (>160°) Subsidiary Shears</i>	<i>Percentage Reduced from Total Map Area</i>
Hemlo	2280.00	5.55	99.70%
Timmins	4106.00	19.04	99.42%
Kirkland	2414.00	24.94	98.70%

GEOLOGIC AND GIS-BASED LODGE-GOLD & VOLCANOGENIC MASSIVE SULFIDE (VMS) MINERAL POTENTIAL MAPS OF A PORTION OF THE ARCHEAN VERMILION GREENSTONE BELT, NORTHEASTERN MINNESOTA

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Lode-gold and VMS mineral potential maps of a portion of the Archean Vermilion greenstone belt in northeastern Minnesota have been developed from the digital incorporation of the lode-gold and VMS ore deposit models into spatial analysis of a new 1:100,000 scale geologic map of the study area. The GIS-based mineral potential models incorporated fuzzy-logic techniques of map combination using variations of knowledge-driven (ore deposit model) and data-driven (analog mining camp analysis) techniques. Inference nets depicting the mineral potential models are presented in Figure 1 (lode-gold model) and Figure 2 (VMS model).

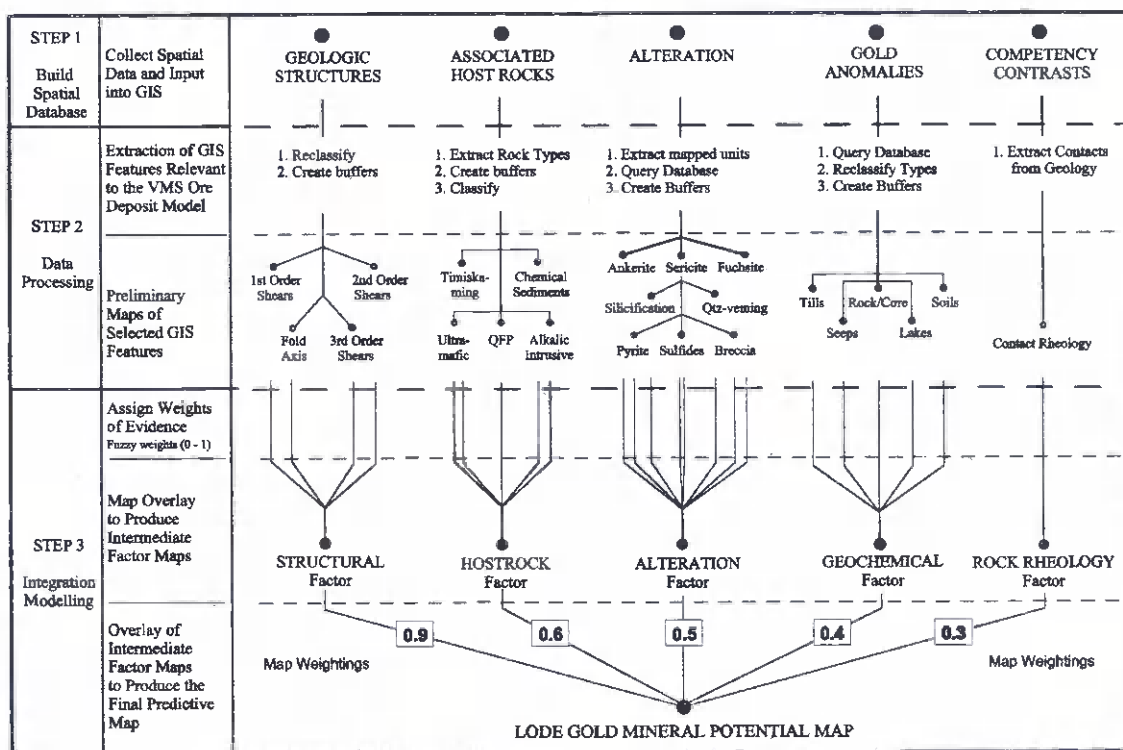


Figure 1. Inference net for the three-step GIS model of the lode-gold mineral potential of the Archean Vermilion greenstone belt, Northeastern, Minnesota. The three steps are: 1) Detailed geologic mapping and compilation of all available geologic data. Conversion of all data into primary GIS datasets; 2) Extracting and enhancing the features of the primary datasets that are important for predicting lode-gold deposits; and 3) Integration of the preliminary maps using GIS modeling techniques that predict mineral potential.

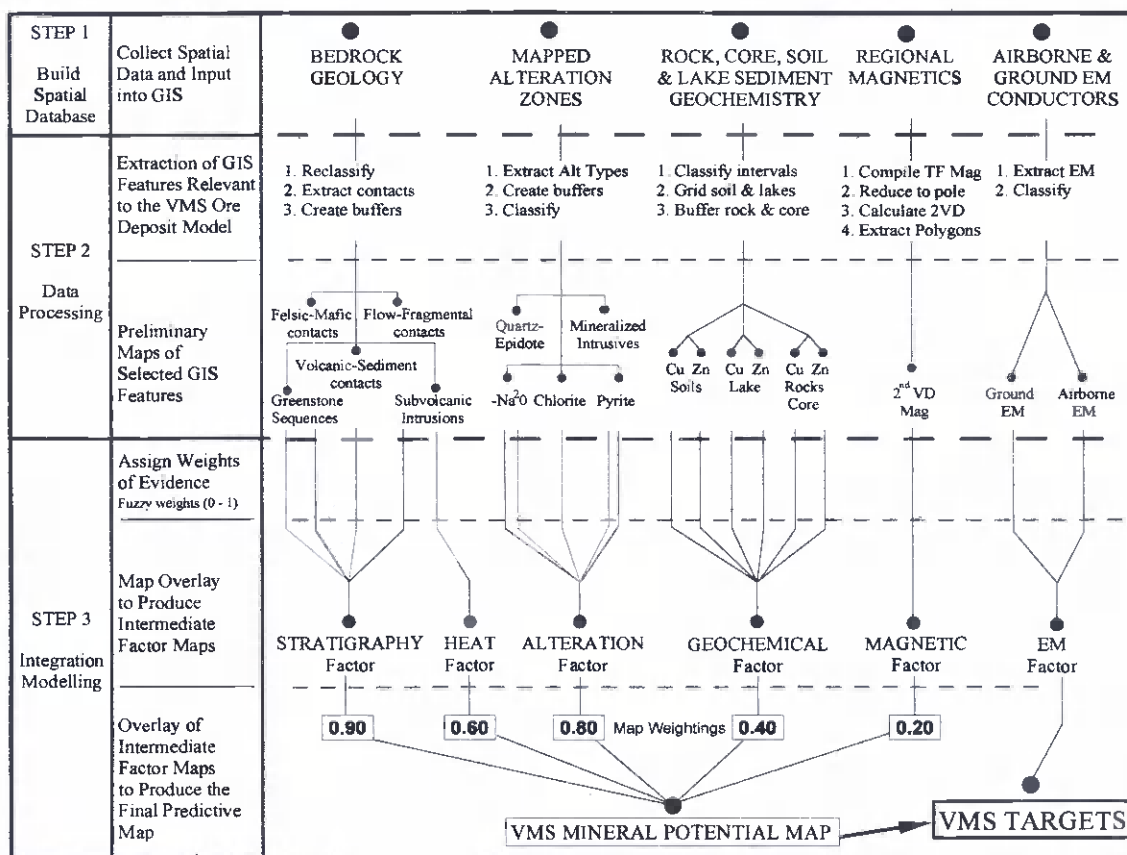


Figure 2 Inference network for the 3-step GIS modeling of the VMS potential of the mineral potential of the Archean Vermilion greenstone belt, Northeastern, Minnesota. The three steps in the study are: 1) Detailed geologic mapping and compilation of all available geological, geochemical, and geophysical data. Conversion of all data into primary GIS datasets; 2) Extracting and enhancing the features of the primary datasets that are important for predicting VMS deposits; and 3) Integration of the preliminary maps using GIS modeling techniques that predict mineral potential.

Unlike similar greenstone belts of the Canadian Shield in Canada, the Vermilion greenstone belt of northeastern Minnesota remains under-explored. One of the main reasons that the area has seen little mineral exploration was due to the discovery of the great iron deposits in the 1870's. Iron companies acquired great tracks of land and essentially prevented precious and base metal exploration for over a century. Recent mapping has shown the presence of very large-scale VMS alteration systems (> 19 km strike length of semi-conformable quartz-epidote alteration) and gold-mineralized shear systems analogous to Archean gold camps in Canada.

The mineral potential maps integrate important geological, geochemical, and geophysical data mapped and compiled by the author with ore deposit models. The ore deposit models have been largely developed from the study of mines within the Canadian Shield and western Australia. Areas on the maps with high modeled VMS and lode-gold mineral potential should be examined in detail by exploration geologists because they possess geologic features indicative of major mining districts.

Samuels Lake Intrusion: A PGE-bearing Quetico-type Intrusion in the Central, Western Quetico Subprovince, Northwestern Ontario

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An array of mafic-ultramafic bodies known as the Quetico intrusions occur along the northern boundary of the Quetico subprovince adjacent to the Wabigoon belt (Fig. 1). This study has identified two previously unrecognised Quetico-type intrusions, the Samuels Lake and Redhorse Lake intrusions, in the central western Quetico subprovince (Fig. 1). The Redhorse Lake intrusion near the US-Canada border is the westernmost identified example of this type of intrusion.

The Quetico intrusions characteristically contain hornblendite, clinopyroxenite, minor apinitite and are accompanied by Cu-Ni-PGE mineralization. Larger intrusions also contain wherlite, gabbro, diorite and syenite. They are distinguished from the mafic-ultramafic intrusions in the Wabigoon and Wawa greenstone belts, such as the Bad Vermilion Lake, Grassy Portage, and Shebandowan complexes, by their lack of associated komatiities and anorthosites.

The 1999 field season consisted of reconnaissance work on the Quetico intrusions along the subprovince boundary and alkaline intrusions surrounding the Samuels Lake intrusion. Grid mapping and sampling were conducted on the Samuels Lake intrusion which was chosen for detailed work due to recent exploration activity and a lack of previous work.

The Samuels Lake intrusion has an NE-SW elliptical form, displaying weak concentric zoning with a wehrlite core partially surrounded by hornblendite and completely surrounded by marginal clinopyroxenite. These units are cut by small dikes and plugs of diorite. The wehrlite and clinopyroxenite phases show a gradational change in modal abundance of constituent minerals. The wehrlite is composed primarily of olivine and clinopyroxene ($Mg\# = 0.83$) with minor phlogopite. Sulphides (pyrrhotite, chalcopyrite and pentlandite) constitute up to 30 vol %. The intergrowth textures of sulphides with olivine and clinopyroxene suggest the separation of immiscible sulphide melt from the parental silicate magma. Low Ni (< 0.06 wt%) in olivine suggests sulphide saturation prior or during olivine crystallization. The clinopyroxenite contains clinopyroxene ($Mg\# = 0.84$) variable amounts of olivine (Fo_{76}) and minor phlogopite with trace sulphides. Hornblendite is composed of euhedral pargasite to magnesio-hornblende, phlogopitic biotite, and plagioclase with trace titanite, pyrrhotite, chalcopyrite, and ilmenite. Diorite consists of plagioclase, magnesio-hornblende, biotite, quartz, and microcline with trace pyrrhotite, chalcopyrite, ilmenite, magnetite, titanite, and zircon.

The Samuels Lake intrusion has undergone high temperature, deuteric processes and low-temperature retrograde alteration. The deuteric phase resulted in the formation of hornblende after clinopyroxene, and the formation of low-Ti magnetite. It may have been accompanied by serpentinization of olivine.

Low temperature alteration produced tremolite-actinolite alteration of hornblende, chlorite after hornblende and biotite, and carbonate alteration. Alteration style and intensity vary between phases and appear to partially control Cu-PGE mineralization. In the clinopyroxenite

phase, Cu-PGE mineralization occurs in areas of intense alteration of the border phase with associated chalcopyrite-rich blebs, inter-fingered with actinolite and calcite. In wehrlite, high levels of PGE mineralization occur in chalcopyrite-rich zones instead of pentlandite-pyrrhotite rich zones. Small chalcopyrite veinlets in wehrlite may contain significant amounts of apatite and with elevated PGE contents. PGE mineralization in the wehrlite phase is associated with the immiscible sulphide liquid, indicating a magmatic origin. In the clinopyroxenite border phase, PGE mineralization is associated with apatite, carbonate and Cu enrichment suggesting that volatile-rich fluid, most likely deuteritic in origin, were responsible for concentration of PGEs.

The Quetico-type intrusions may not be restricted to the Quetico belt. The east-west trending array of intrusions may be extended eastward into the Wabigoon subprovince to include Lac Des Milles Lac, Demar Lake, Taman Lake, Legris Lake, Lac Des Iles, and Tip Gabbro mafic-ultramafic intrusions (Fig. 1). These intrusions have similar lithological assemblages to the Quetico intrusions. The mineralization observed in Samuels Lake and other Quetico intrusions are also similar to that in the clinopyroxenite phase of the Roby zone in the 2692 $\pm$ 4/-2 Ma Lac Des Iles mafic-ultramafic complex. If this correlation is supported by geochronology in progress, it will establish that the Quetico and Wabigoon subprovinces were proximal by 2692 Ma.

Figure 1. Simplified geological map of Western Wabigoon, Quetico, and Wawa subprovinces. Solid, finely dashed line outlines the distribution of similar mafic-ultramafic intrusions across the Quetico-Wabigoon subprovince boundary.

PETROGENESIS OF THE ENIGMATIC AURORA SILL, MESABI RANGE, MINNESOTA

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The syenitic Aurora Sill intrudes the Biwabik Iron-formation of the Mesabi Range in northern Minnesota. Since the work of White (1954), the sill has commonly been assigned a Mesoproterozoic (Keweenawan) age because of its resemblance to "red rocks" associated with the Midcontinent Rift in the Duluth region. The age of the sill is important to understanding the timing of ore formation in the Mesabi Range. In 1999, Morey proposed a conceptual model in which the high-grade ores formed in a regional ground-water system during Paleoproterozoic time. Subsequently, Graber and Strandlie (1999) argued that nearby high grade ores must have formed in Mesoproterozoic or later time, because the Aurora Sill appears to have controlled ore-forming processes in nearby mines. New data from this study imply that the Aurora Sill is quite different, both mineralogically and geochemically, from known felsic rocks in the Midcontinent Rift. Thus, the age of the sill remains uncertain and the possibility exists that it was intruded soon after deposition of the Biwabik Iron-formation in the Paleoproterozoic (ca 1878 Ma; Fralick, 1998).

The Aurora Sill extends approximately 5.6 km along the Mesabi Range north of the town of Aurora and ranges in thickness from 6 to 37 m (White, 1954). The sill was recently exposed during mining operations in the NW 1/4, NE 1/4, sec 3, T58N, R15W. Due to the inaccessibility of the exposures along vertical walls in the mine, samples were collected from large blocks along a bench immediately above the sill. In all, ten samples were studied from this locality along with seven samples from core (16.4-38.1 m in depth) drilled in the NW 1/4, NE 1/4, sec 2, T58N, R15W. Fine-grained, porphyritic syenite from the margin of the sill exhibits trachytic texture; medium- to coarse-grained syenite in the interior of the sill lacks aligned plagioclase. Sodic plagioclase (albite) occurs as phenocrysts (3.0-7.0 mm) and microcrysts (0.2-1.0 mm) and is extensively altered. Mafic minerals in fine-grained samples include small (0.1-0.3 mm) and euhedral aegirine; fibrous amphibole and chlorite are common in the coarse-grained samples. Other minerals are K-feldspar, Fe-Ti oxides, Fe sulfide, and zircon. The presence of two feldspars indicates subsolvus crystallization at high P_{H_2O} .

Coarse-grained samples contain 50 modal percent sodic plagioclase and 5-20 modal percent K-feldspar and are classified as syenite and alkali-feldspar syenite. CIPW norm compositions of these rocks include 68-82 percent alkali feldspar (Or + Ab), 5-10 percent plagioclase (An), and as much as 5 percent nepheline; they are classified as nepheline-bearing alkali syenite or nepheline-bearing syenite. Fine-grained samples from along the margin of the sill contain 74-84 percent normative alkali feldspar (Or + Ab) with small amounts (<4%) normative quartz and are classified as alkali feldspar syenite.

Samples from the Aurora Sill exhibit little geochemical variation ($SiO_2 = 54.6-60.7$ wt. percent; $Mg\# = 0.40-0.75$; $Y = 9-19$ ppm) suggesting that the intrusion has undergone relatively little internal frac-

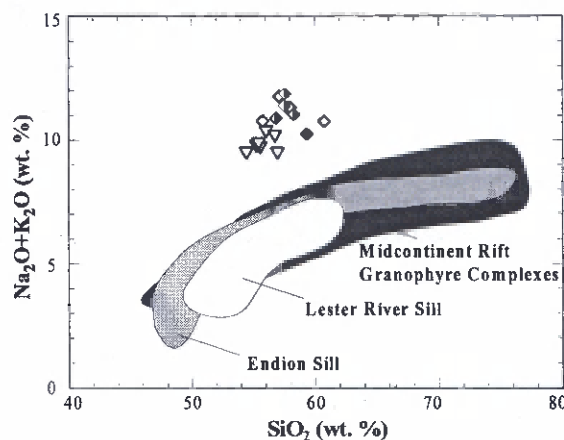


Figure 1. Na_2O+K_2O (total alkalis) versus SiO_2 comparing Aurora Sill rocks with those of the Endion Sill, Lester River Sill (Green, 1972; Jerde, 1991), Midcontinent Rift granophyre complexes (Kennedy et al., this volume), and granophyric dikes of the Dunka River region (Harris and Wirth, this volume). Symbols: inverted triangles = drill core; diamonds = mine (open = fine-grained; half-filled = medium-grained; filled = coarse-grained).

tionation. All of the samples exhibit high Al_2O_3 concentrations and are peraluminous to metaluminous. There appears to be no correlation between structural position in the sill and composition. Marked differences exist in the concentrations of some elements (e.g., K_2O and SiO_2) between drill core and mine samples. Such differences could reflect different degrees of alteration or fractionation along the length of the sill. Alternatively, the differences might reflect the presence of two separate intrusions, but this is considered unlikely because these sample localities are well within the 5.6 km expanse of the sill as defined by White (1954).

The Aurora Sill is distinct from the felsic complexes of the Midcontinent Rift in several respects. The sill lacks the granophyric textures and quartz that are typical of felsic rocks of the Midcontinent Rift. The sill is weakly saturated to undersaturated in silica and contrasts sharply with the silica-saturated rift-related granophyres. Furthermore the Aurora Sill is characterized by high total alkalis (Figure 1), Nb/Y (Figure 2), and Ce/Zr compared with felsic rocks of the Midcontinent Rift. The sill also lacks the negative Nb anomalies that are characteristic of the Midcontinent Rift granophyres. This property suggests that the sill was derived from a mantle melt that did not interact significantly with crustal materials. The high Nb and Rb, low-Y composition of the sill is typical of within plate granites (Pearce, 1984), consistent with emplacement in the Animikie foreland basin. Nd isotope and U-Pb zircon studies are in progress and should provide additional constraints on the petrogenesis and age of the Aurora Sill (Phillips, in prep).

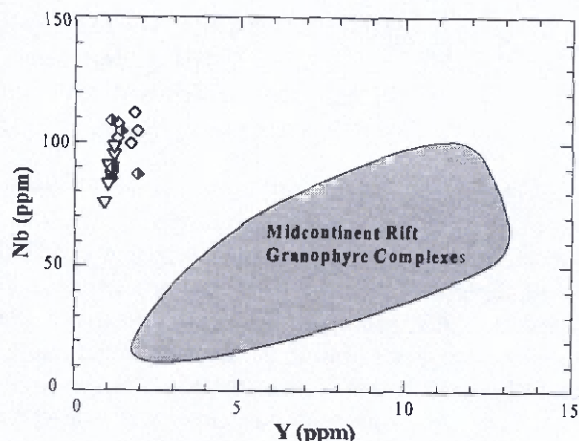


Figure 2. Nb versus Y plot comparing Aurora Sill samples with analyses of Midcontinent Rift granophyre complexes (Kennedy et al., this volume). Symbols as in Figure 1.

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Low-grade metamorphic zonation of the Keweenaw Portage Lake Volcanics on the Keweenaw Peninsula, Michigan

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The metamorphic-hydrothermal alteration and mineral assemblages of the Portage Lake Volcanics (PLV) on the Keweenaw Peninsula in Michigan have been studied over the last ten decades due to the occurrence of native copper deposits. Jolly & Smith (1972) illustrated for the first time the existence of a systematic zeolite-prehnite-pumpellyite sequence in the PLV. In their Eagle Harbor drill core profile they identified a zonation from zeolite facies in the upper part of the section to a prehnite-pumpellyite facies in stratigraphically lower parts. In this study, three diamond-drill core profiles (Fig. A) through the PLV were re-examined using a combination of different techniques such as electron microprobe analysis and special X-ray powder diffraction techniques. The profile include the Ahmeek, the Copper Harbor, and the Eagle Harbor profile and penetrate 5000 m of vertical section in the PLV, and are spaced over a distance of 50 km. The profiles were correlated using characteristic interflow sediments and selected lava flows as marker horizons.

Macroscopic and microscopic examination of 614 samples indicate at least three and possibly up to five different stages of alteration based on the various amygdule infilling sequences that can be differentiated during the deposition and subsequent tilting history of the PLV. A vertical as well as lateral zonation is observed in the PLV on the Keweenaw Peninsula. From the approximately southwest to the northeast, three different low-grade metamorphic zones can be observed. In the vicinity of the former copper mining region and adjacent to the Keweenaw Fault, a pumpellyite-prehnite facies, also with abundant epidote is observed. Further to the north and stratigraphically below the Greenstone Flow a pumpellyite-prehnite facies is present. The flows above the Greenstone Flow and further to the northeast toward the Keweenaw Tip show a zeolite facies with laumontite, phyllosilicates (mainly clinocllore) and calcite.

The alteration of the PLV starts with the filling of small (<3 mm) vesicles and the lining of larger vesicles with phyllosilicates (alteration stage 1). During deposition and subsequent burial metamorphism of the sequence (alteration stage 2), Section C and D (Fig.: A + B) experienced conditions of the pumpellyite-prehnite facies (assemblage pumpellyite-prehnite-epidote-albite) which is the highest observed in the sequence. The beginning thrusting-event of the PLV combined with the formation of the Keweenaw Fault tilts the PLV. A new alteration stage 3 with a fluid probably originating from the Lake Superior syncline now crosscuts and overprints the earlier burial metamorphic stage

2, especially in the Section A and B. Afterwards a new NNW-SSE directed fracture system was set up on the Keweenaw Peninsula. Along these fracture zones a hyper salinar ore containing fluid deposited in open pore space quartz, native copper and calcite (alteration stage 4) under conditions similar to the temperature conditions of alteration stage 3. The low-grade metamorphic history of the Keweenaw Peninsula ends with a meteoric, cold and low salinity fluid that precipitates the final calcite and late zeolites in veins and still open amygdules (alteration stage 5).

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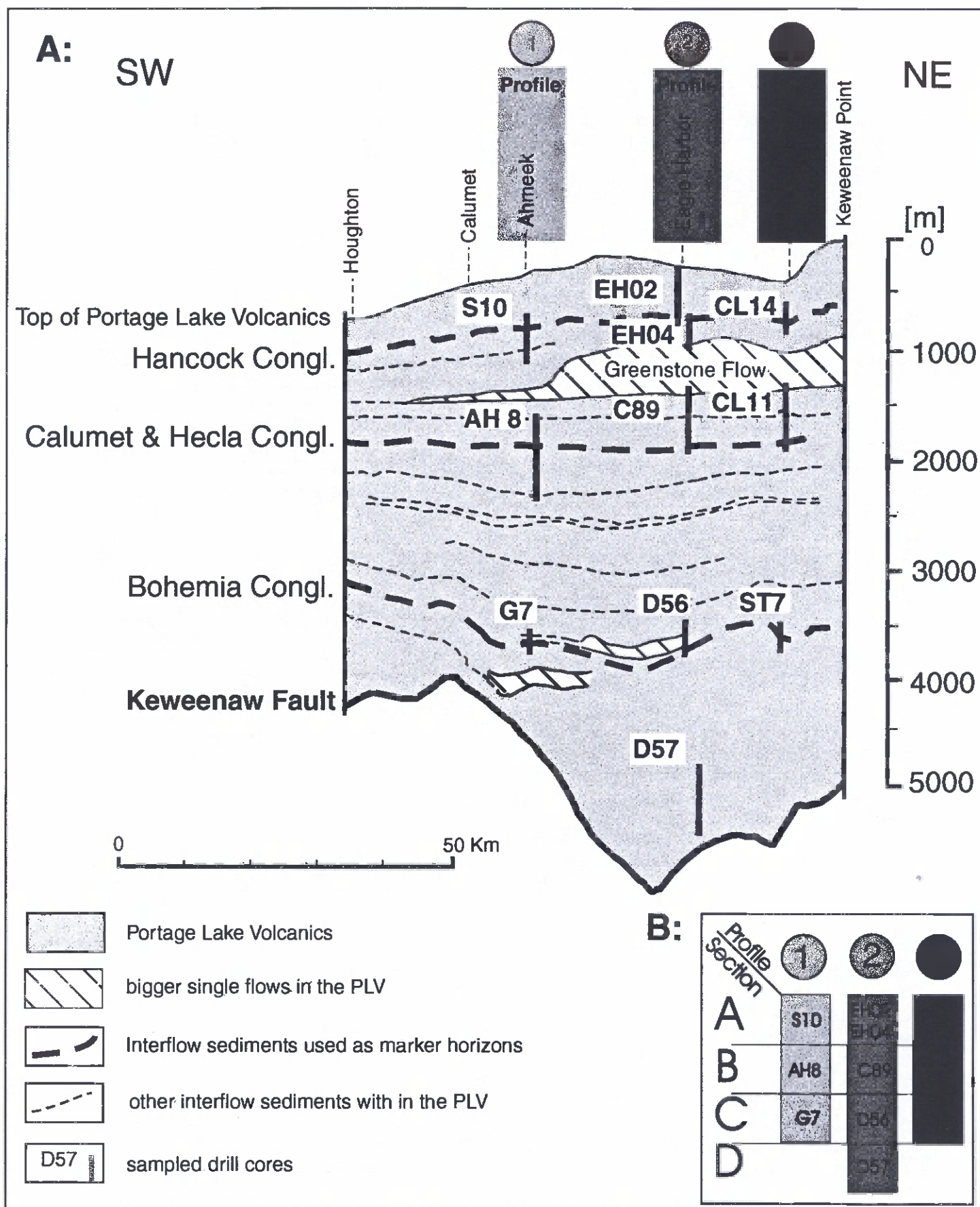


Figure:

A: Back rotated stratigraphic cross-section of the Portage Lake Volcanics (PLV) along strike from Houghton in the southwest to the Keweenaw Point in the northeast. With the sampled drill cores and appropriate marker horizons. (Modified from Paces 1988)

B: Simplified sketch of cross-section for easy reference.

Modeling the effect of intermediate temperature (350°-500°C) Mazatzal-age thermal overprinting on argon diffusion in hornblende from the southern Lake Superior region.

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Mica Ar/Ar ages from the southern Lake Superior region leave little question that much of the Penokean orogenic belt was thermally and deformationally overprinted by Mazatzal (ca. 1650 Ma) orogenic activity to the south (Holm et al., 1998; Romano et al., 2000; Loofboro and Holm, 1998). Complete resetting of mica argon systematics from bedrock samples beneath 1750-1630 Ma deformed quartzites suggests widespread heating to temperatures above 350°C during Mazatzal-related metamorphism. Hornblende Ar/Ar ages from within the deformed region (Romano, 1999; Mancuso, 2000) are predominantly younger than the Penokean Orogeny, scattering from 1800-1638 Ma (Fig. 1). Three of the hornblende separates analyzed were completely reset, probably by localized hydrothermal fluid-related activity associated with the Mazatzal Orogeny. Romano et al. (2000) have postulated that the scatter of the other post-Penokean hornblende ages (over a 70 m.y. interval) reflect variable retention of radiogenic argon associated with episodic loss after initial closure during Penokean time. In order to test this hypothesis, we have modeled various thermal histories by imposing peak temperature excursions from 350°-600°C over orogenic timescales (20-80 m.y.). The effectiveness of diffusion in resetting Ar/Ar ages is primarily a function of the peak temperature and its duration; the model results are fairly insensitive to choice of initial and final conditions (Loofboro and Holm, 1998).

The results of modeling (Fig. 2) suggests that the distribution of hornblende Ar/Ar ages (Fig. 1) is consistent with the partial resetting of argon systematics at ca. 1650 Ma by thermal pulses reaching maximum temperatures between 350° and 460°C. A recent petrologic investigation of the deformed Baraboo quartzite indicates metamorphic temperatures of 320°-390°C (Medaris et al., 1998). We do not consider it improbable, therefore, that bedrock regions underlying the deformed quartzites reached even higher temperatures (between 400° and 460°C) during Mazatzal-age overprinting. The modeling suggests that a combination of elevated temperatures (350°-460°C with gradients in T_{max}) and localized fluid-activity associated with Mazatzal deformation provide the simplest explanation for preservation of the scattered Penokean, intermediate, and Mazatzal hornblende age data (Fig. 1).

We present a conceptual model for Mazatzal orogenic overprinting of the southern Lake Superior region (Fig. 3). The geometry we depict for collision of the Mazatzal province is in concert with that recently proposed for Mazatzal collision in the southwest U.S.A. (Selverstone et al., 1999) and accounts for southward vergence of folds in the Baraboo quartzite (Dalziel and Dott, 1970). Our results corroborate the hypothesis proposed nearly 20 years ago by Dott (1983) that the severity of quartzite deformation in Wisconsin was related to collision from the south at ~1630 Ma.

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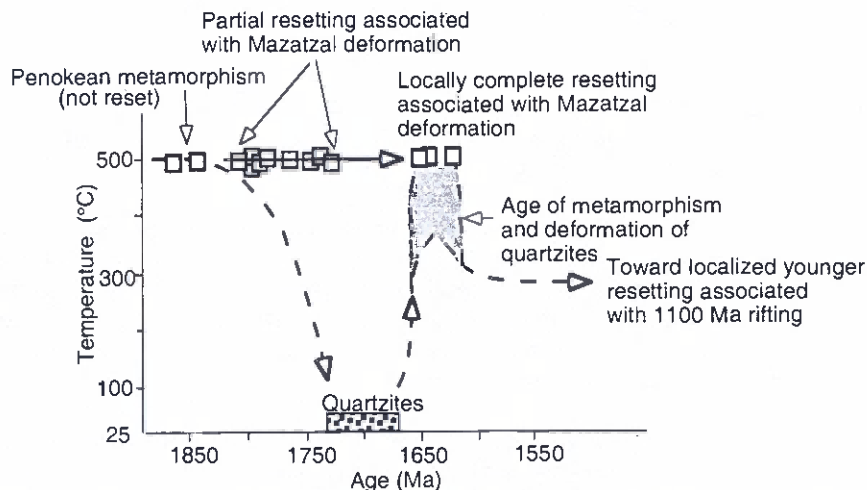


Figure 1. Summary of hornblende Ar/Ar dates from bedrock south of the Mazatzal-age thermal front (after Romano, 1999, and Mancuso, 2000). Temperature-time path modified after Romano et al. (2000). Note gap in spread of hornblende dates between 1733 and 1646 Ma.

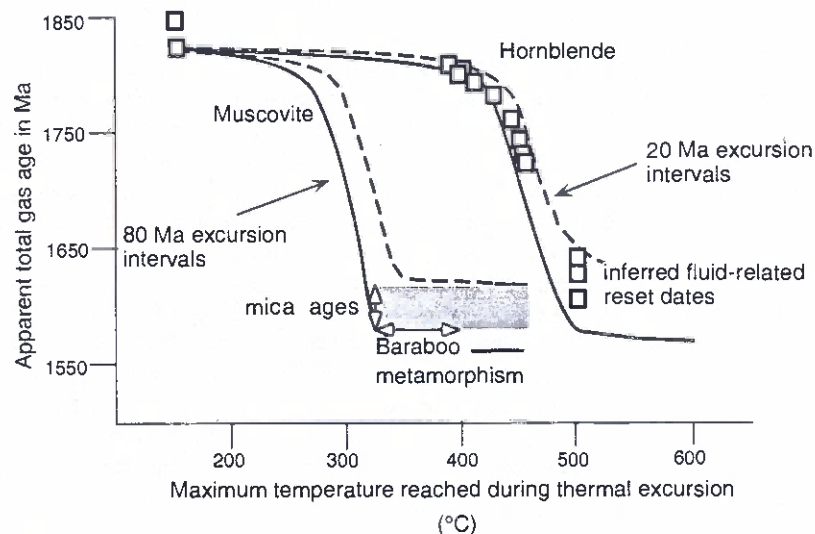


Figure 2. Results of modeling a Mazatzal-age (1650-1600 Ma) thermal overprinting on minerals which initially cooled shortly after the Penokean orogeny (1850-1830 Ma). Dashed curves show effect on apparent age data for 20 m.y. temperature excursions at various peak temperatures. Solid lines for 80 m.y. excursions. Squares represent hornblende age data as in figure 1. Stippled region depicts the temperature range necessary to thermally reset hornblende to the degree indicated by the hornblende age data.

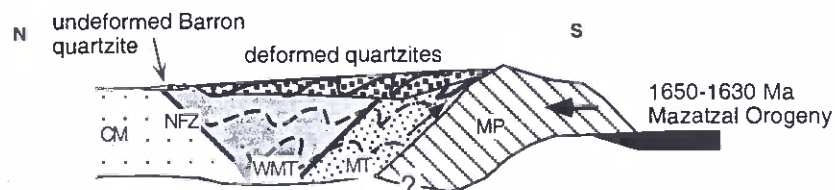


Figure 3. Conceptual model (no scale) for the Mazatzal orogeny and its effects in the southern Lake Superior region. Modified after Romano et al., 2000. Collision causes crustal-scale deformation, south-verging folds, and heating of much of the Penokean orogenic belt. CM is continental margin, MT is Marshfield terrane, MP is Mazatzal province, NFZ is Niagara fault zone, WMT is Wisconsin magmatic terrane.

THE 'SANDOR' DIAMOND OCCURRENCE, MICHIPICOTEN GREENSTONE BELT, WAWA, ONTARIO (a preliminary study)

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The "Sandor" diamond occurrence is the first discovery of a bedrock diamond source in the Michipicoten region since veteran prospector "Mickey" Clement reported in 1993 the presence of alluvial diamond in the Michipicoten River to the Ontario Geological Survey.

A xenolith-bearing lamprophyre dike was observed by veteran prospector Sandor Surmacz and Geologist Marcelle Hauseux along highway 17 in Lalibert Township north of Wawa, Ontario on June 22, 1993 (S. Surmacz, Prospector, personal communication, 1997). Exploratory work was being conducted in the area under an Ontario Prospector Assistance Program (OPAP) grant. Diamond indicators were not found but a sample for geochemical analysis returned results interpreted as unfavorable for the presence of diamond (S. Surmacz, Prospector, personal communication, 1997).

Surmacz and Hauseux resampled the Wawa dike in 1995. The sample was sent to the Saskatchewan Research Council's diamond recovery laboratory and 6 gem diamonds recovered (press release, KWG Resources Inc., June 6, 1996; S. Surmacz, Prospector, personal communication, 1997). The ground was claimed from the Algoma Central Railroad and optioned to Spider Resources Inc. (S. Surmacz, Prospector, personal communication, 1997).

The occurrence represents a unique discovery of diamond in Archean (2703 ± 42 Ma, L. Heaman, University of Alberta, unpublished data) rocks of non-kimberlite composition. The dikes are commonly characterized by rounded mafic xenoliths up to 1 metre in size set in a fine grained groundmass. The xenoliths are commonly widely spaced throughout the lamprophyre dike but in some dikes the xenoliths may be densely packed. The xenoliths weather in positive relief and commonly are enveloped in a dark biotite-rich reaction rim up to several centimeters in width. The dikes have been subjected to regional metamorphism and tectonism and the xenoliths altered to an actinolite-talc-carbonate assemblage. Primary mineralogy and texture are not preserved in the matrix or xenoliths. Geochemically the dikes approximate a basalt or mildly alkalic basalt magma and the xenoliths pyroxenite. These diamondiferous dikes are concentrated in the northwest-central region of the Michipicoten Greenstone Belt largely restricted to a synformal anticline centered in Lalibert Township. The dikes are concentrated near and east of the Dickenson Lake syenite stock, but a genetic relationship between the stock and dikes remains to be firmly established. The dikes are both conformable and crosscutting to the deformed supracrustal stratigraphy. The lamprophyre dikes are up to 5 m in width and cannot be traced any great distance in the bush covered terrain. Diamond is distributed erratically in the dikes and only 10 % of the dikes have yielded diamond.

The dikes do not contain mineral compositions characteristic of kimberlite and are not a likely source for the kimberlite indicator minerals found in the region. Geophysical methods have proven ineffective in locating the dikes. The presence of actinolite and anomalous Cr and Ni contents in the soils are the most effective prospecting techniques.

Lithogeochemistry and Paleotectonic Setting of the Bend Massive Sulfide Deposit, Northern Wisconsin

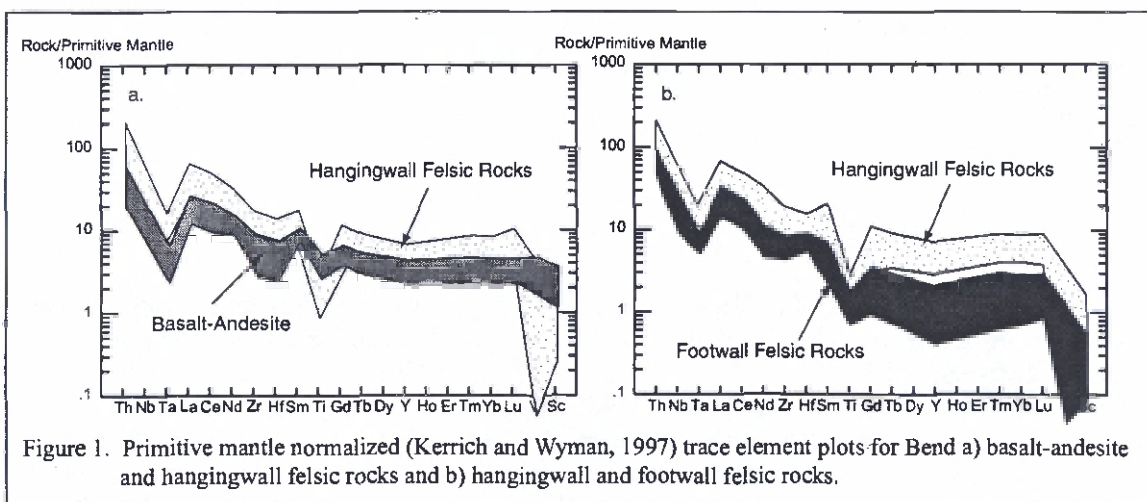
Klaus J. Schulz and Suzanne W. Nicholson
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The Bend massive sulfide deposit is located in Taylor County, Wisconsin, approximately 19 miles north-northwest of Medford, in the Chequamegon National Forest. Exploration conducted between 1985 and 1994 by the former Jump River Venture, and more recently by Sharpe Energy and Resources, identified 3.9 million short tons of ore grading 1.87% copper, 0.09 opt gold, and 0.39 opt silver (DeMatties and Rowell, 1996). We conducted a geochemical study of the volcanic section hosting the massive sulfide deposit using 90 samples collected from drill core. The study emphasized interpretation of stable trace elements (e.g., REE, Zr, Hf, Ta, Ti) to help determine primary magmatic affinities and the tectonic setting of the volcanic section hosting the Bend deposit.

The Bend massive sulfide deposit occurs in a felsic volcanic-dominated sequence, located along the southern flank of a mafic volcanic succession (DeMatties, 1994). The felsic volcanic sequence is up to 2000 feet thick, steeply dipping, south facing, and lower greenschist facies. The stratigraphic footwall consists of bedded felsic tuffs (sericite schist) with interbedded quartz-crystal tuffs (quartz-sericite schist) overlain (stratigraphic hangingwall) by mafic to felsic feldspar-phyric lava flows, felsic volcanoclastic layers, and associated fine tuffs and sediments. Alteration, consisting of silicification, sericitization, and sulfidation, is most intense near the massive sulfide, particularly in the footwall sericite and quartz-sericite schist. Mafic to intermediate dikes and sills (?) are present locally.

The Bend volcanic sequence ranges from basalt through andesite to dacite-rhyodacite with dacite-rhyodacite most abundant. Both the mafic and felsic rocks are calc-alkaline in character with decreasing FeO_t and high La/Yb (>15) and Th/Yb (>0.65) ratios (i.e., Barrett and MacLean, 1999). Mafic rocks, mostly andesite with minor basalt, are characterized by enriched light-REE ([La/Yb]_n ~ 6), relatively flat heavy-REE, prominent depletion of Ta, Zr, Hf, and Ti, and enriched Th on a primitive mantle normalized plot (Fig. 1a). Relatively unaltered hangingwall felsic volcanic rocks partly overlap compositionally with the most evolved andesites but have slightly greater enrichment in light-REE (i.e., [La/Sm]_n ~ 3-4 vs ~2-3 for the andesites) and no to small negative Eu anomalies. On a primitive mantle normalized plot the hangingwall felsic rocks show patterns similar to the andesites with prominent depletions in Nb, Ta, and Ti, lesser depletion of Zr-Hf, and enriched Th (Fig. 1a). The hangingwall dacite-rhyodacite was probably derived through fractionation of plagioclase+pyroxene+Fe-Ti oxide from the andesite.

Footwall sericite and quartz-sericite schist show compositional effects of alteration with more variable SiO₂, higher K₂O/K₂O+Na₂O, and higher S content than most hangingwall felsic rocks; footwall samples also show increasingly positive Eu anomalies with increasing S content. The footwall felsic rocks mostly have depleted heavy-REE and generally lower trace element abundances than hangingwall felsic rocks (Fig. 1b). Although the heavy-REE depletion in the footwall samples could be a result of alteration, some samples with depleted heavy-REE show no compositional evidence of significant alteration (e.g., no high S content and/or high K₂O/K₂O+Na₂O ratio). Also, studies of REE mobility associated with alteration below massive sulfide deposits have identified mobility of light- and middle-REE but general stability of the heavy-REE (Barrett and MacLean, 1999). Thus, the compositional difference between footwall and hangingwall felsic rocks may reflect primary differences.



The Bend volcanic rocks plot as a typical orogenic calc-alkaline basalt-andesite-dacite-rhyodacite suite on various compositional discrimination diagrams (e.g., Th-Hf-Ta; Th-Tb-Ta; Th/Yb-Ta/Yb). Further, the enriched light-REE and high Th of the Bend suite are characteristic of orogenic sequences in continental settings (Barrett and MacLean, 1999). A continental setting is also supported by the abundance of felsic calc-alkaline volcanic rocks in the Bend sequence. In addition, the volcanic rocks hosting the Bend massive sulfide deposit are similar compositionally to those in the Monico area in north-central Wisconsin that host the Pelican deposit (Sims and others, 1989). Neodymium isotope data for felsic volcanic rocks in the Monico area have negative epsilon Nd indicating a contribution from an enriched crustal source. The lithogeochemistry suggests that the Bend deposit and probably other massive sulfide deposits associated with felsic centers in northern Wisconsin (e.g., Flambeau, Pelican, Crandon) evolved in an extensional continental setting, possibly a continental back-arc basin in a southward-directed subduction system.

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Assessing the extent of Early Proterozoic Penokean versus ~1770-1760 Ma metamorphism in east-central Minnesota

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Combined field, geophysical, and drill core data from the internal zone of the Penokean orogen in Minnesota have greatly increased our knowledge of this orogen's architecture, allowing new correlations with the Wisconsin magmatic terranes to the east (Jirsa et al., 1995). Low-grade, greenschist metamorphic, structural panels have been identified as arcuate, imbricate thrust sheets in the poorly exposed, southeast portion of the zone (Jirsa and Chandler, 1997). To the west and north, these structural panels have been intruded by abundant post-tectonic granitoids that make up a physically continuous mass of bedrock over 7000 km² (Figure 1). Holm et al. (1998) have documented widespread post-Penokean (1770-1760 Ma) amphibolite facies metamorphism in the plutonic region. Our goal is to determine the extent of Penokean and/or ~1760 Ma metamorphism within the lower-grade terranes to the southeast.

We have dated five mineral separates from recently obtained drill core housed at the Minnesota Geological Survey. Sample localities and associated dates are plotted on figure 1 together with results from prior thermochronologic studies (Southwick, 1994; Holm and Lux, 1996; Holm et al., 1998). Biotite from a biotite-hornblende granodiorite (EC-8) intruded by the post-tectonic Foley batholith yielded a plateau age of 1846±6 Ma (four age increments constituting over 75% of the gas released). In spite of its proximity to the Foley intrusion, this rock was apparently unaffected by it thermally. Biotite from a biotite schist (EC-22) sampled east of the Foley batholith yielded a plateau age of 1863±7 Ma (eight age increments constituting over 72% of the gas released). Biotite from a tonalitic orthogneiss (EC-27) yielded a plateau age of 1820±7 Ma (seven increments, 81% of total gas released). A hornblende separate from the same drill core sample of orthogneiss yielded a plateau age of 1831±6 Ma (seven increments; 64% of total gas released). Lastly, hornblende from a meta-quartzdiorite (EC-16) yielded a plateau hornblende date of 1838±5 Ma (seven increments, 81% of total gas released). Only one other Penokean Ar/Ar age on hornblende has been reported from east-central Minnesota (1854±5 Ma plateau date on the Philbrook pluton; Southwick, 1994). Five previously published hornblende Ar/Ar dates from the plutonic terrane all yielded post-Penokean dates of ~1760 Ma (Holm et al., 1998).

This is the first study to document biotite Penokean Ar/Ar cooling ages in east-central Minnesota. These data firmly establish a Penokean age of metamorphism for the lower grade structural panels described by Jirsa and Chandler (1997). While preliminary, these data also indicate no significant thermal overprinting at either ca. 1760 Ma (as documented to the northwest in the plutonic terrane) or at ca. 1630 Ma (as long documented in adjacent parts of the orogen in Wisconsin). It appears the 1770-1760 Ma barrovian amphibolite metamorphism in the internal zone of east-central Minnesota may be restricted to the deepest exposed region which also contains abundant post-tectonic plutons. If so, this would be consistent with the interpretation of Holm et al. (1998) that the deepest exposed region was probably the thickest portion of the Penokean orogenic belt which became unstable and rapidly collapsed (i.e., unroofed) at ~1760 Ma. The temporal and spatial association of post-tectonic plutons, barrovian ~1760 Ma metamorphism, and midcrustal unroofing suggest a genetic link between thermal softening of the overthickened crust and post-orogenic collapse in the hinterland of the Penokean orogen.

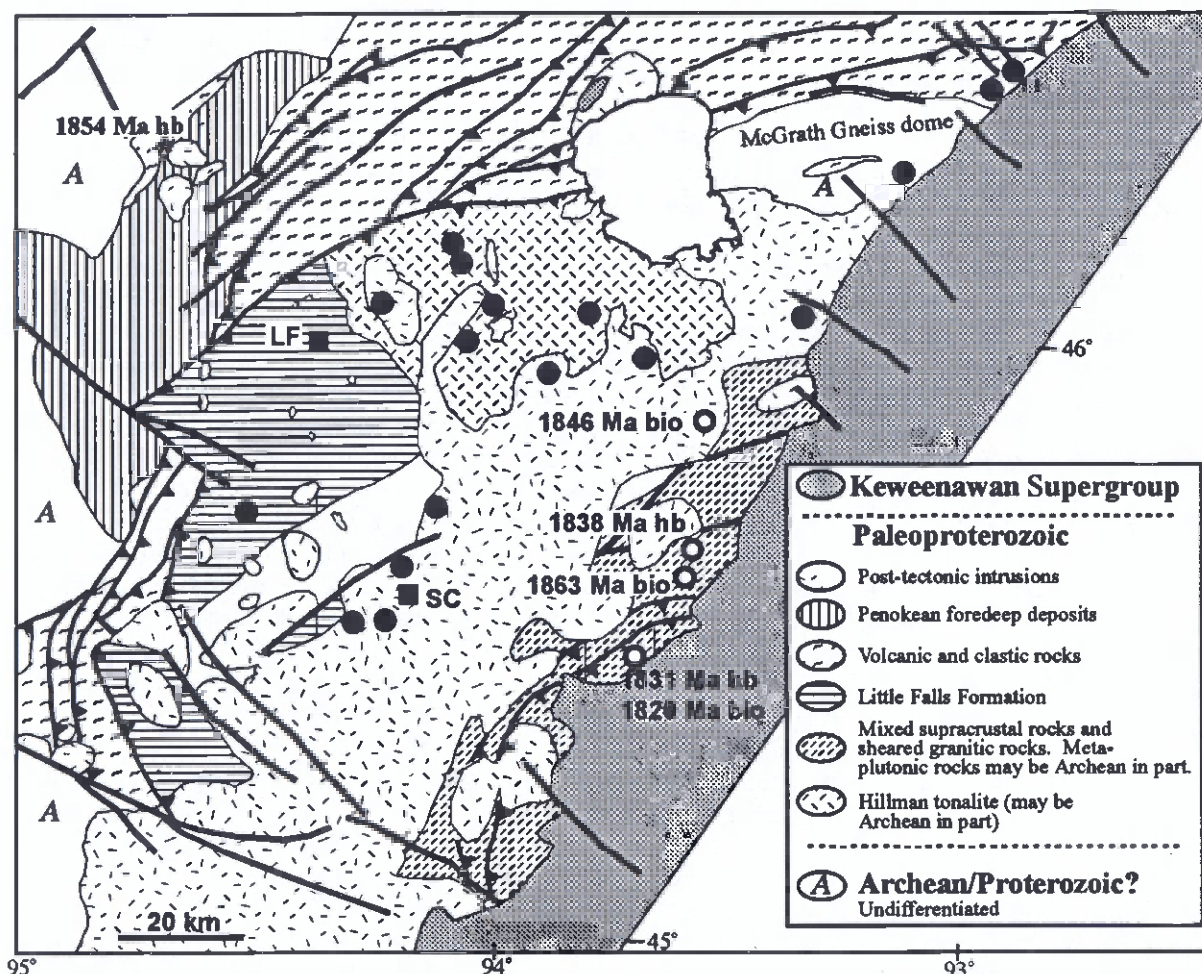


Figure 1. Generalized bedrock geology map of east-central Minnesota. Filled circles represent localities of prior results (after Holm and Lux, 1996; Holm et al., 1998) which yielded ca. 1760-1750 Ma dates on mica and hornblende. Also plotted is the 1854 Ma Ar/Ar plateau age on hornblende from the Penokean Philbrook pluton (Southwick, 1994). Open circles represent localities and results from this study. LF is Little Falls, SC is St. Cloud.

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THE DISTINCTION BETWEEN FLAT PEBBLE CONGLOMERATES AND INTRAFORMATIONAL BRECCIAS IN PRECAMBRIAN IRON FORMATIONS

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Iron formation, a distinctive type of rock restricted largely to the Precambrian, consists mainly of silica (in the form of chert) and such iron-rich minerals as hematite, magnetite, siderite, and/or greenalite. Lamination and thin bedding are commonplace in these rocks as evidenced by the near-universal use of the term BIF (for "Banded Iron Formation"), but a substantial minority of iron formations (particularly those in North America) are actually GIF (for "Granular Iron Formation"). Such units have coarsely clastic textures (analogous to those of carbonate grainstones and oolites) and display structures such as cross-bedding rather than banding. Centimeter- to decimeter-scale layers rich in siliceous, flat, pebble-size fragments are minor constituents of both BIF and GIF. The fragments are clearly intraformational in origin and are frequently cited as evidence of deposition in shallow, high-energy environments in both settings, but they have very different origins. The fragments in GIF occur in flat pebble conglomerates where they generally have well-rounded ends, form a grain-supported framework, and originated via erosion and reworking at the sediment-water interface. In contrast, the fragments in BIF occur in breccias where they are generally much more angular, isolated in a matrix of less siliceous material, and originated after deposition and at least shallow burial via partial liquefaction. The dominance of cherty fragments in both breccias and conglomerates indicates that silica-rich layers were significantly more cohesive than silica-poor ones in both BIF and GIF. Many of the flat pebbles in GIF are identical to nodular masses known as chert pods in underlying sediments, suggesting they are exhumed nodules. Petrographic evidence such as large differences in minus-cement porosity inside vs. outside the pods and dramatic thinning of individual layers as they exit pods indicates the pods formed via early silica cementation. This widespread early cementation is probably due to high silica concentrations in Precambrian seawater which, unlike today, caused silica to diffuse into (rather than out of) sediment pore waters (Siever, 1992, *Geochimica et Cosmochimica Acta* 56, 3265-3272).

PRECAMBRIAN FEATURES UNDER THE JAMES BAY AND HUDSON BAY LOWLANDS

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Large parts of the Superior Province underlie the Phanerozoic cover of both the James Bay and Hudson Bay lowlands. This, plus the poor bedrock exposure in the eastern and northernmost exposed Sachigo Subprovince, has permitted only limited success to date in correlating the regional geology of the Uchi-Sachigo superterrane with parts of the Superior Province in northwestern Quebec. A project is planned to examine a number of geological problems in addition to regional correlations by reprocessing the ODM/GSC aeromagnetic data of the 1960s covering the region mainly north of Latitude 51°. This will be done in co-operation with Regional Geophysics staff of the GSC. This poster is intended to outline some of the Precambrian features under the lowland cover that might be enhanced when the reprocessing is completed.

Features and Interpretive issues:

- 1) The complex, broad high magnetic susceptibility that characterizes the substrate of the northern Hudson Bay Lowlands [HBL] is similar to that of the Pikwitonei granulite domain and adjacent domains in Manitoba. We suspect that this region of old crust, containing a broad range of Archean ages including pre-3.8 Ga crust (cf. Böhm et al., *Geology*, Jan/00), continues into the northernmost part of Ontario and underlies the early Proterozoic Sutton Inlier.
- 2) Elements of the Trans-Hudson Orogen [THO] are exposed in parts of Manitoba and the HBL. Re-interpretation of the aeromagnetic patterns that characterize this region suggests several points to consider:
 - a) The Proterozoic Fox River Belt of Manitoba does not appear to continue eastwards across the northern HBL but continues north to Hudson Bay near the Manitoba-Ontario border and probably links to the Internides of the main THO linear gravity anomaly just offshore, north of Ontario.
 - b) Strata from the Trans-Hudson Orogen offshore in Hudson Bay seem to reappear as folded units north of the Sutton Inlier and discontinuously extend southwards towards the inlier. These features need further discrimination to establish their full extent.
 - c) The Sutton Inlier has for many years been treated as a single, continuous package of rock as currently portrayed on geological maps (compiled from the original work by H. Bostock - GSC Paper 70-42). But a closer examination of the aeromagnetic patterns in its vicinity suggests the Sutton Inlier is not a single large domain but a set of southward-convex-shaped inliers strung along a line. They resemble "klippe-like" features comprising shallow water platform sedimentary deposits including iron formation, and gabbroic sills that might have been transported southwards onto the Archean craton from the main THO belt offshore. Smaller "klippe" are also aeromagnetically apparent to the north and east of the currently defined Sutton Inlier. The strata resemble the Nastapoka Formation on the eastern shore of Hudson Bay (cf. Chandler and Parrish, *Prec. Res.* 1989) and part of the Povungnituk Group of Cape Smith Belt.
- 3) Beneath the James Bay Lowlands [JBL], there is a strong likelihood that the English River and Quetico metasedimentary subprovinces converge under the James Bay Lowland cover and that the Wabigoon Subprovince pinches out eastwards. Discrimination of this has important tectonic implications for the original nature of these subprovinces. It is compelling to suggest that the converging English River and Quetico resemble telescoped inter-arc basins that wrap around the east end of a Wabigoon microcontinent and continue on-line with the Nemiscau R. and Opinaca R. "basins" in Quebec. The merged English R - Quetico is conceptually analogous to the modern basins of the Solomon and Coral seas respectively north and south of east Papua-New Guinea.
- 4) The Sachigo and Uchi subprovinces of northwestern Ontario appear to merge under the eastern HBL and JBL and continue eastwards as a single domain and emerging as the Minto domain of northern Quebec.
- 5) A major indenter-like feature occurs under the eastern HBL, flanked to the west by a fault similar in orientation to the Miniss Fault. This feature, like other "indenters" in northwestern Ontario (e.g., at Savant Lake, Shebandowan and Manitouwadge), closes northwards and borders a "bow-tie" aeromagnetic pattern on its north flank, which appears to reflect shortening and exhumation of deeper crust.

THE 1787-1772 MA EAST-CENTRAL MINNESOTA BATHOLITH: PRECURSOR TO CRUSTAL STABILIZATION IN THE L. SUPERIOR REGION

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The cause of ~1760 Ma magmatism in the southern L. Superior region has been considered enigmatic because of its apparently abrupt nature and the considerable amagmatic hiatus (~60 m.y.) that separates it from Penokean orogenesis. The age of post-Penokean magmatism in Wisconsin, commonly referred to as "1760 Ma", was obtained by dating mg-sized fractions from rhyolites and epizonal granites (Van Schmus, 1980). We report here new U-Pb data from the recently characterized midcrustal plutonic terrane in east-central Minnesota. This portion of the exposed Penokean orogen contains numerous post-tectonic plutons of varying composition and geometry (Jirsa et al., 1995; Boerboom et al., 1995; 1998). Based on field, drill-core, petrologic, and geophysical studies, about 20 separate intrusive bodies have been identified and categorized into four separate groups: 1) granodioritic to dioritic rocks; 2) gray granites; 3) red granite plutons, dikes and sills; and 4) late mafic plugs and diabasic to quartzofeldspathic dikes.

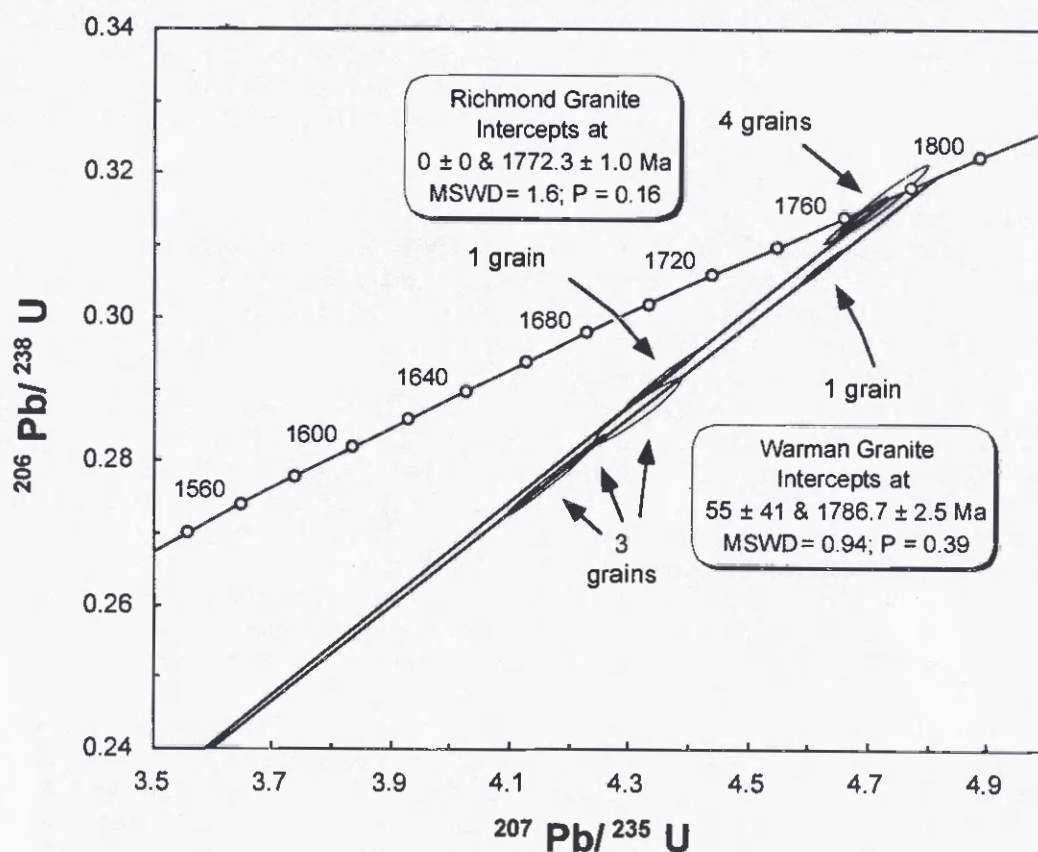


Figure 1. Plot of zircon data from the younger and older ends of the age spectrum for the East-Central Minnesota batholith. Data for other units fall in between these two populations.

Our new results are mostly U-Pb isotope dilution analyses from single zircons weighing 1 to 5 micrograms, with several hand-picked, air-abraded grains selected for each rock unit. For the most part the analyses are not influenced by xenocrystic cores, although in a few cases they may be present. All units of the post-tectonic suite, the "East-Central Minnesota batholith" (ECMB), yield ages within the range 1772 ± 1 Ma (Richmond Granite) to 1787 ± 3 Ma (Warman Granite). The relative ages within this range correlate with relative ages based on field relationships (where known). Thus, all units of the ECMB (St. Cloud Red Granite, Reformatory Granodiorite; Rockville Granite, Freedham Tonalite, Anne Lake Granite, plus others) were emplaced within 15 m.y. In addition to the ECMB, we are determining ages from surrounding basement rocks, using outcrop and drill core samples; preliminary results yield an age of 1800 ± 8 Ma for a foliated tonalite within the Hillman migmatite complex. We are also redetermining U-Pb ages of several units of the "1760 Ma" suite in Wisconsin using single-crystal analyses, but at this time our data are not definitive.

Our results suggest that the "1760 Ma" magmatic event is only the last stage of a ~25 m.y. episode of post-tectonic magmatism. These data significantly reduce the time-lag between the end of Penokean orogenesis and the onset of post-tectonic plutonism, bringing it into line with thermal and physical models which predict characteristic time-lags of only 20-40 m.y. (England and Thompson, 1984; Turner et al., 1992).

Intrusion of the ECMB was associated with widespread midcrustal amphibolite metamorphism and directly preceded rapid exhumation (i.e., collapse?) and crustal stabilization (Holm et al., 1998). In some regions of incipient collapse (i.e., India-Asia today), the overthickened crust contains a partially molten layer ponded in its mid-section (Nelson et al., 1996). In analogous manner we suggest the overthickened Penokean crust was invaded by midcrustal melts which probably affected its rheological behavior. Vast magma intrusion may have dramatically decreased crustal viscosity and promoted collapse (as recently proposed for the Canadian Cordillera; Vanderhaeghe et al., 1999).

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ISOTOPIC CONSTRAINTS ON THE ORIGIN OF GRANOPHYRE COMPLEXES IN THE MIDCONTINENT RIFT OF NORTHEASTERN MINNESOTA.

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The magmatism of the Midcontinent Rift (MCR) is dominantly mafic in composition in both the volcanic sequences as well as the underlying intrusive rocks. In some portions of the MCR, however, the magmatism is strongly bimodal with significant volumes of rhyolite and granite in association with basalt and gabbro [1]. This is particularly true for the northeast limb of the North Shore Volcanic Group (NSVG) where approximately 25% of its 6.4 km thick volcanic stratigraphy is composed of rhyolite and other evolved lavas [2]. Evolved intrusive rocks are also prominent in the northwest flank of the MCR and occur in compositionally stratified complexes. Although these are dominantly granitic (granite-granodiorite) in composition, intermediate rocks (monzodiorite-quartz monzodiorite) predominate in the lower portions of these complexes. Collectively these have been termed granophyres because of their characteristic granophyric textures. The field relations, petrography, and geochemistry of these complexes are described by Kennedy et al. [3].

The granophyres have striking geochemical similarities to the overlying volcanic rocks. Both have a strong bimodal character illustrated by the compositional gap at ~ 58-67% SiO_2 (Fig. 1). The chemistry of the rhyolites and the granites are similar in many respects (e.g., major and trace elements, REE patterns) which begs the interpretation that the granophyric complexes represent the magma chambers that supplied the large rhyolitic eruptions.

The NSVG lavas are isotopically heterogeneous (Fig. 2). Most basalts have initial ϵ_{Nd} values close to zero or slightly negative [4, 5]. The rhyolites, in contrast, typically have strongly negative initial ϵ_{Nd} values (down to -15) indicating they were formed in large part by the partial melting and assimilation of older (most likely Archean) crustal rocks.

In contrast to the NSVG lavas, the granophyres are more isotopically homogenous both individually and collectively (Fig. 2). With one exception all granophyres have initial ϵ_{Nd} values 0 to -5, similar to most basalts in the MCR [7]. The isotopic homogeneity of individual granophyres is demonstrated by the compositions of two granophyre complexes (Misquah Hills and Greenwood Lake) located in central

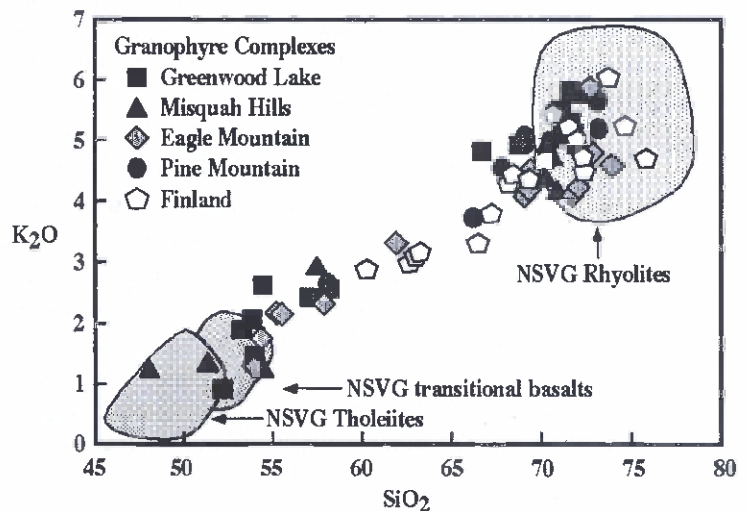


Figure 1. SiO_2 vs. K_2O plot illustrating the linear array and bimodal distribution of the granophyre compositions. Also shown are data for NSVG tholeiitic and transitional basalts [5] and rhyolites [6]. Few samples (4 of 5 are from the Finland granophyre) plot in the SiO_2 gap (58% to 67%).

Cook County. The Greenwood Lake granophyre ranges from monzodiorite to granite (SiO_2 52% to 72%) but has initial ϵ_{Nd} values of -0.7 to -1.9 (Fig. 2), an extremely small range considering analytical reproducibility (± 0.3 to $0.4 \epsilon_{\text{Nd}}$ units). The Greenwood Lake granophyre was emplaced during the early stage of the MCR (1107 Ma; [8]). The Misquah Hills granophyre has not been dated but is likely of similar age because it intrudes a sequence of older, reversed polarity lavas.

These new isotopic data, in conjunction with major and trace-element chemistry and previously published Nd results from 6 other granophyres [6], provide important constraints on the origin of the granophyre complexes.

First, the granophyres are isotopically distinct from the rhyolites. Although two of the Cook County rhyolites (Kimball Creek, Red Rock) have initial ϵ_{Nd} values about -5, this is more negative than all but one of the granophyres (Eagle Mtn., initial $\epsilon_{\text{Nd}} = -7.7$). This indicates that the granophyres are probably not genetically related to the rhyolite flows and do not represent the magma chambers from which the rhyolites were fed. It is important to note, however, that the granophyres most thoroughly studied thus far (Misquah Hills, Greenwood Lake) are likely older (~ 1107 Ma). It is not until the main stage of the rift (< 1100 Ma, [9]) that the large rhyolites with the highly negative ϵ_{Nd} values were erupted in the NSVG.

Secondly, the two granophyres examined thus far show remarkable isotopic homogeneity. This implies that these complexes have been derived from a single parental magma or from magmas that are isotopically similar. In the case of the granophyre complexes, the high silica portions could not have been derived to a significant extent from melting or assimilation of older crust. Rather, it is more probable that the limited isotopic variations within the granophyre complexes were produced by fractionation and mixing processes with only minor assimilation. It remains possible that the granitic rocks have been derived by partial melting and cannibalization of crystallized MRS magmas lower in the crust, but this seems unlikely considering the refractory nature of such rocks and the availability of less refractory older crust present in the lower crust, especially during early stages of rifting.

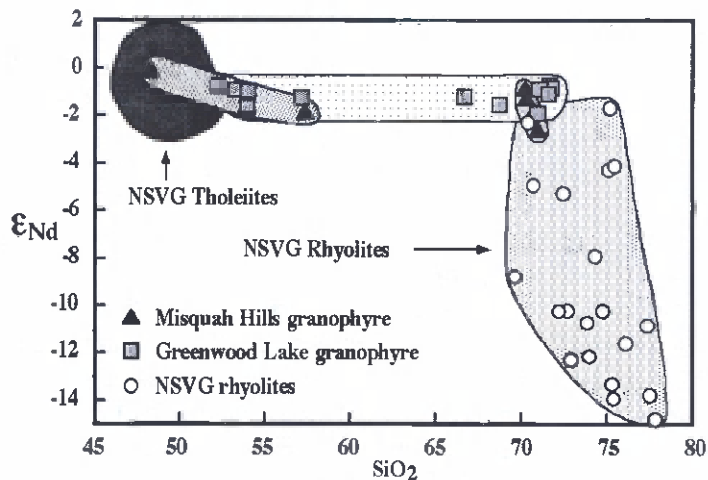


Figure 2. SiO_2 vs. initial ϵ_{Nd} of the granophyre complexes. Also shown are data for NSVG tholeiitic basalts [5] and rhyolites [6]. Note the Nd isotopic homogeneity of the Misquah Hills and Greenwood Lake granophyres over a wide range of SiO_2 .

References: [1] J.C.Green, 1982, *Geol. Soc. Am. Mem.*, **156**, 47. [2] J.C.Green and T.J.Fitz, *J. Volcan. Geotherm. Res.*, **54**, 177 (1993). [3] B.C.Kennedy, K.R.Wirth, and J.D.Vervoort, this volume. [4] J.C.Brannon, Ph.D. thesis, St. Louis Univ. (1984). [5] L.Dosso, Ph.D. thesis, Univ. Minn. (1984). [6] J.D.Vervoort and J.C.Green, *Can. J. Earth Sci.*, **34**, 521 (1997). [7] S.W.Nicholson, S.B.Shirey, K.J.Schulz, and J.C.Green, *Can. J. Earth Sci.*, **34**, 504 (1997). [8] D.W.Davis and J.C.Green, *Can. J. Earth Sci.*, **34**, 476 (1997). [9] J.D.Miller and J.D.Vervoort, *ILSG abstr.*, (1996).

ARCHEAN DIAMOND EXPLORATION TARGETS IN THE MICHIPICOTEN GREENSTONE BELT, WAWA, ONTARIO

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Traditionally, diamond exploration in Ontario has focussed on following KIM dispersion trails and on examining geophysical targets believed to be related to kimberlite pipes. However, the 1993 announcement of the discovery of three alluvial diamonds recovered from the Michipicoten River area south of Wawa has led to the search for much different diamond sources.

In 1995, S. Surmacz and M. Hauseux made the first discovery of Archean-aged bedrock occurrence of diamonds in Ontario in Lalibert Township, approximately 20 kilometers north of the town of Wawa. Following this announcement, Spider Resources discovered nine more diamondiferous dikes in the same geographic region in 1997. Early this year, Ban-Ore Resources Ltd. announced the discovery of at least one more diamondiferous dike (the GQ Occurrence), this time in Musquash Township. To date, 5 commercial stones, 42 macrodiamonds and 338 microdiamonds have been recovered from bedrock in an area approximately 30 square kilometers in size.

Presently, there appear to be two types of Archean diamond-bearing bedrock in the area. The "Sandor-type" dikes are mafic in composition and contain up to 35% spectacular actinolite+talc+carbonate xenoliths ranging up to 1 metre in size. The fine-grained matrix is foliated. These rocks have been classified as lamprophyres. These dikes are detailed in another featured poster by R. P. Sage of the Ontario Geological Survey in Sudbury.

The second type of dike, the GQ-type, is more strongly foliated than the first type and very closely resembles the intermediate to felsic tuffs that host them. The matrix is fine-grained, actinolite-rich and up to 60% subangular, supracrustal xenoliths have been observed in the dikes. These rocks have yet to be classified.

Both types of dikes are typically narrow (0.1 – 10 m wide) and their maximum length is unknown. The dikes trend both northeast and northwest and, as yet, seem to display no readily recognizable geophysical signature. Both types of dikes are metamorphosed and are presumed to be slightly older than the supracrustal rocks that they intrude. The KIM signature associated with these occurrences is unusual in that there are no chrome diopsides or chrome pyrope garnets related to the dikes. Chromite and ilmenite are the only two indicator minerals presently thought to be associated with these occurrences.

These dikes are concentrated in the central part of the Michipicoten greenstone belt and are related to a synformal anticline centred on Leclair Township. These dikes appear to be related to a nappe structure lying on the northwest shoulder of the Kapuskasing Structural Zone.

The recent discovery of Archean-aged diamondiferous dikes within the Kapuskasing Structure in Ontario has significantly influenced diamond exploration in the province.

DIAMONDS AND DIAMOND EXPLORATION IN NORTHERN ONTARIO WITH A FOCUS ON THE MICHIPICOTEN GREENSTONE BELT, WAWA, ONTARIO

WILSON, A. C., Ministry of Northern Development and Mines, Ontario Government Complex, Highway 101 East, P. O. Bag 3060, South Porcupine, Ontario, P0N 1H0 (705-235-1614; ann.wilson@ndm.gov.on.ca)

Since 1899, it has been postulated that the source of the alluvial diamonds found south of Lake Superior originated east or west of James Bay. Blue (1899) made this suggestion based on the fact that many of the gravels and boulders found in the glacial drift of Wisconsin, Michigan and Ohio, for example, are identical in composition and structure to the materials north of the Great Lakes.

The first reported occurrence of diamond in bedrock, in Ontario, was in 1914. Microscopic diamonds were reported by the Ontario Department of Mines in a sample collected from the claims of D. O'Connor in Reaume Township, located approximately 32 kilometers north of Porcupine.

Exploration for diamonds in Ontario began in earnest in about 1960 when the presence of diamond indicator minerals (KIMs) was discovered by Selco Exploration in the Moose River drainage basin. The first confirmed kimberlite was discovered in Hogg Township by Aquitaine Company of Canada in 1974.

The James Bay Lowlands have been a diamond exploration hotspot since the late 1980's and has continued to be a favourite exploration target up to the present. Exploration has involved companies such as KWG Resources, Spider Resources, Ashton Mining of Canada, Continental Precious Metals, Garde Mining Exploration, B. P. Resources Canada Ltd. and Monopos Ltd. Exploration has led to the discovery of several kimberlite clusters, the most notable being the cluster situated in the Attawapiskat River area. During the winter of 1999-2000, Monopros Ltd. has been in the process of extracting a 10,000 tonne bulk sample from the Victor kimberlite pipe.

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The recent discovery of Archean-aged diamondiferous dikes within the Kapuskasing Structure in Ontario will significantly influence the way that future diamond exploration is conducted in the province.

Blue, A. 1899. Are there diamonds in Ontario?; *in* Report of the Ontario Bureau of Mines 1900, p.119-124.

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PETROGENESIS OF THE SILVER CREEK DIKE: A 1.1 Ga INTRUSION IN THE MIDCONTINENT RIFT

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The Silver Creek dike is a mafic intrusion exposed along Lake Superior at Silver Creek cliff north of Duluth, Minnesota. Silver Creek cliff is comprised of several lava flows of the North Shore Volcanic Group, which the dike intrudes, and a thin overlying sill. Previous misinterpretations of Silver Cliff as a single sill were the result of an unseen upper contact, a contact that is now clearly exposed as the result of a tunneling project in the early 1990s.

Samples from field work and drill cores taken during the tunneling project have been analyzed for both major and trace elements. Major element data from both XRF analysis and microprobe work indicate that the Silver Creek dike is a diabase consisting predominantly of labradorite, augite, olivine, and Fe-Ti oxides. The rare earth element (REE) pattern of the dike's upper chill zone mimics that of the overlying flows suggesting contamination in the upper part of the dike. REE patterns of the lower chill zone, however, show it to be a primitive olivine tholeiite with no significant contamination. Isotope data indicates that the Silver Creek dike formed from a relatively primitive and uncontaminated mantle magma with ϵ_{Nd} values near 0.

Geochemical Impacts of An Undisturbed Mineral Deposit – Results From the Bend Deposit, Chequamegon National Forest, Wisconsin

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The Bend copper-gold massive sulfide deposit in the Medford District of the Chequamegon National Forest, Taylor County, Wisconsin, is hosted by Early Proterozoic volcanic rocks. Pre-Pleistocene saprolite and 100-120 feet of Quaternary materials cap the mineralized horizon. Ore consists of massive pyrite with varying amounts of chalcopyrite, tetrahedrite-tenantite, bornite, arsenopyrite, chalcocite, and rare gold-silver tellurides. The ore zone at Bend contains significant concentrations of arsenic, bismuth, mercury, tellurium, thallium, and antimony in addition to the principal ore metals, copper and gold. Because these elements are atypical of surrounding bedrock, the Bend deposit was selected to examine natural elemental dispersion from a buried massive sulfide in a glaciated region. The influence of the Bend mineralization on its environment is characterized using a geochemical database that includes: 1) bedrock, massive sulfide and saprolite obtained from diamond drill core provided by Sharpe Energy and Resources and the Jump River Joint Venture; 2) regional samples of Quaternary materials from Taylor County (Attig, 1993); and 3) subsurface Quaternary material and weathered bedrock from the area of the Bend deposit obtained by rotasonic drilling.

The USGS drilled five rotasonic drill holes through the Quaternary deposits along a 0.5 mile linear transect that crossed the strike of the Bend mineralized zone. Nearly continuous core was recovered from every borehole, including up to several feet of weathered bedrock. The core reveals a complex Quaternary section that consists of two till sheets, several intervals of gray, clay-rich lake sediments, and several areas of outwash. The older till is gray, carbonate-rich till of the Marathon Formation and the younger is reddish brown till of the Copper Falls Formation. The Marathon Formation both underlies and overlies lake sediments and outwash. Bedrock in the area of the Bend deposit is directly overlain by the lowermost outwash unit, whereas the Marathon Formation is draped over metagabbro that forms a bedrock high to the south of the deposit. Detailed geochemical analyses of the different units show that in addition to obvious color and grain size distinctions, higher average Ca content also distinguishes the Marathon Formation from the Copper Falls Formation.

As much as 20 meters of saprolite is preserved over massive sulfide at the Bend deposit. Saprolite is leached of most metals that are concentrated in unweathered massive sulfide. Cu, Zn, Au, As, Se, and Te concentrations all decline sharply across the transition from massive sulfide to saprolite, whereas Ba, Mn, Ti, Cr, Ni, and V increase markedly. Anomalous concentrations of those elements within the massive sulfide are mostly lacking in overlying glacial deposits suggesting that the saprolite cap prevented physical dispersal of sulfide rock by glacial movement. However, in the glacial deposits directly over the Bend mineralization, relatively high values of Hg and Au are found. This suggests hydromorphic dispersion of these elements from massive sulfide. In the down-

ice direction from the Bend deposit, gold concentrations are found increasingly higher in the Quaternary section (Figure 1). The overall pattern for Hg is less distinct, although Hg values found in both Marathon Formation and Copper Falls Formation tills from rotasonic core are markedly higher than Hg values measured in regional subsurface samples from the same formations.

This study shows that although regional background geochemical values in glacial deposits can be influenced by anomalous concentrations of elements in bedrock, the nature of both the sources and the sinks for various elements controls the dispersion patterns. It also shows that understanding the character of the subcrop of a massive sulfide and the intervening surficial stratigraphy is critical in geochemical exploration in this terrane. In the case of the Bend deposit, metal-depleted saprolite caps the deposit and has protected massive sulfide from glacial dispersion, so sulfide-bearing boulders and traditional metal (such as Cu and Zn) anomalies have not developed even in till near the bedrock surface. However, more subtle dispersion patterns of other elements may indicate the presence of sulfide mineralization.

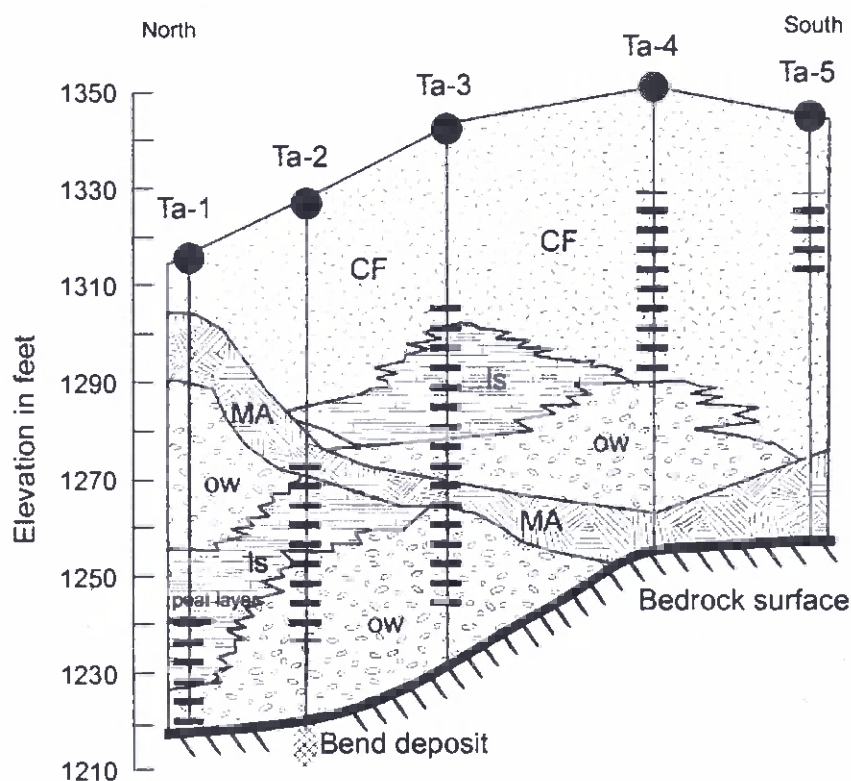


Figure 1: Cross-section of the surficial section in the area of Bend deposit. CF = Copper Falls Formation, MA = Marathon Formation, ow = outwash, ls = lake sediments, Ta designates each rotasonic drill hole. Striped areas show locations of samples with greater than .01 ppm Au. Vertical and horizontal dimensions are not to scale.

Reference: Attig, J. W., 1993, Pleistocene geology of Taylor County, Wisconsin: Wisconsin Geological and Natural History Survey Information Circular 65, 27 p.