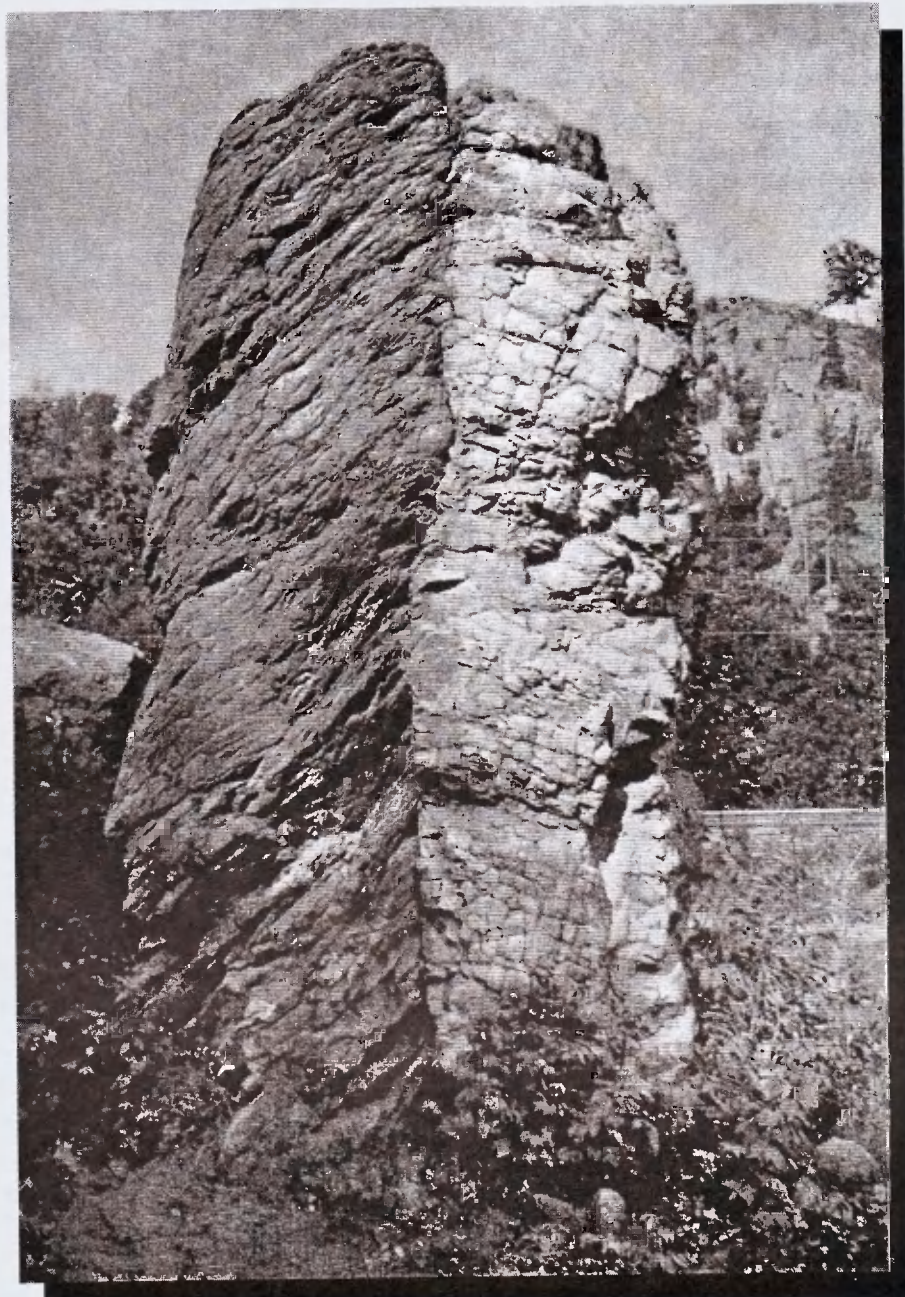


47th Annual Meeting Institute on Lake Superior Geology

**Proceedings Volume 47
Part 1—Program and Abstracts**



Madison, Wisconsin ♦ May 9–12, 2001

INSTITUTE ON LAKE SUPERIOR GEOLOGY

**47th Annual Meeting
May 9-12, 2001
Madison, Wisconsin**

Hosted by:

**University of Wisconsin-Extension
Wisconsin Geological and Natural History Survey**

**University of Wisconsin-Madison
Department of Geology and Geophysics**

**Proceedings
Volume 47**

Part 1 - Program and Abstracts

47th Annual Meeting Institute on Lake Superior Geology

Volume 47 contains the following parts:

Part 1: Program and Abstracts

Part 2: Field Trip Guidebook

- 1 - Sedimentologic, Tectonic and Metamorphic History of the Baraboo Interval:
New Evidence from Investigations in the Baraboo Range, Wisconsin
- 2 - Geology, Ore Deposits, and Cultural History of the Upper Mississippi Valley
Zinc-Lead District
- 3 - Economic Geology of the Baraboo and Waterloo Quartzites
of Southern Wisconsin

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Mark Jirsa
Minnesota Geological Survey
2642 University Avenue
St. Paul, MN USA 55114-1057
(612) 627-4780
email: jirsa001@tc.umn.edu
ILSG website <http://www.ilsgeology.org/>

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Van Hise Rock, Abelmans Gorge, SW1/4, sec. 28, T21N, R5E, Sauk County, Wisconsin from Salisbury, R.D., and W.W. Atwood, 1900, The Geography of the Region About Devil's Lake and the Dalles of the Wisconsin: Wisconsin Geological and Natural History Survey Bulletin V, Plate IX.

Charles R. Van Hise and Charles K. Leith used this outcrop as a laboratory to demonstrate the fundamental geometric relationship between slaty cleavage and bedding at an outcrop-scale for inferring larger-scale structures. See Field Trip Stop 4, this meeting, Part 2, p. 17.

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INSTITUTES ON LAKE SUPERIOR GEOLOGY, 1955-2001

#	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
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
47	2001	Madison, Wisconsin	M.G. Mudrey, Jr., B.A. Brown

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.

AN OBITUARY FOR SAMUEL S. GOLDICH

By Bruce R. Doe

Goldschmidt Medal winner in 1983, Samuel Stephen Goldich died 20 December 2000 at his apartment in Applewood, Colorado (a suburb of Denver), less than a month before his 92nd birthday. Sam, as he was widely known, received early fame with his 1938 paper in the *Journal of Geology* on rock weathering based on his Ph.D. thesis, an amazing paper that continued to receive citations into the 1990s, more than 50 years later. In short, he determined that the resistance of igneous minerals to weathering was the inverse of the Bowen Reaction Series, that is minerals crystallized at lower temperatures were more resistant to weathering than those crystallized at high temperatures (and pressures). In other words the last minerals to crystallize (e.g., the most resistant was quartz followed by orthoclase, etc.) from a melt were the most resistant to weathering, a sequence that became known as the Goldich Stability Series (for a short discussion of this on the web see the 1996 web site of Pamela Gore at <http://www.dc.peachnet.edu/~pgore/geology/geo101/weather.htm>). A few years later in 1941, a second, two-part widely utilized paper was published by Sandell and Goldich on the trace-element concentrations in igneous rocks, also in the *Journal of Geology*. This pioneering paper introduced the dithizone colorimetric analytical technique for trace-element determination to earth science and resulted in some of the most precise trace-element data in extent at the time and for decades thereafter.

Sam got into an argument with the late Paul Gast over which radiometric dating system on biotite would be more susceptible to alteration by weathering -- the K-Ar system or the Rb-Sr system -- and a bet ensued. Paul thought that K-Ar would be more affected by weathering which would open the structure of biotite and let the argon escape which was not bound in the structure. Sam, however, thought that Rb-Sr would be more affected because the Sr that did not fit in the structure would be subject to ion exchange. Thus a paper resulted (Goldich and Gast, 1966). Incidentally, Goldich won the bet. A very important paper with Mudrey (first presented in abstract form at the Geological Society of America meeting as Goldich and Mudrey, 1969, with the paper appearing in 1972) using dilatancy to help explain the discordance of the U-Th-Pb ages in zircons never received the acclaim it deserved because of its original publication in a Russian book, but Doe was later to make use of it in explain the U-Th-Pb whole-rock

system in granites. In brief, the theory says that as the



pressure on minerals and rocks is released through uplift and erosion, they expand and make lead that is not in the structure accessible to removal by crustal fluids. No biography of Goldich would be complete without mention of Sam's interest in the 3,500-myr.-old rocks of the Minnesota River Valley which originally appeared to be 3,800 myr. old in his collaborations with Ed Catanzaro and later Tom Stern (see Goldich, Hedge and Stern, 1970). This discovery led to the search of other areas in the U.S. for perancient rocks with the discovery by others of these sorts of rocks in Michigan and Wyoming. He ended his research career with a very important paper on the air abrasion method of preparing zircons for U-Th-Pb dating (Goldich and Fischer, 1986) that has become much used for Pb isotope tracer work as well as zircon dating. Sam received the Department of Interior Distinguished Service Award in 1965, and he was a founder of the Institute of Lake superior Geology and received its first Goldich Award in 1980.

S.S. Goldich received an AB from the University of Minnesota in 1929 and eventually a Ph.D. in 1936. In between, he earned an M.A. from Syracuse University in 1930 (and was to receive their Alexander Winchell Award in Geology in 1977), spent two years as an assistant in geology at the then Missouri

School of Mines, 1930-1932 (now, University of Missouri at Rolla) where his association with Garrett Muilenburg resulted in his first paper (Muilenburg and Goldich, 1933), and was a fellow at Washington University in St. Louis where he published a paper with Carl Tolman (Tolman and Goldich, 1935). While a graduate student at the University of Minnesota, he was a chemist in the famous Rock Analysis Laboratory. In the period 1936- 1941, Sam rose from instructor to Associate Professor at the Texas Agricultural and Mechanical College which resulted in a number of papers on Texas geology and developed his research interest in iron ore in a paper with Barnes, Goldich, and Romberg (1949) that resulted in the milestone papers with Henry Lepp (Lepp and Goldich, 1959, 1964). He served World War II in the U.S. Geological Survey in exploration and study of laterite and bauxite in a number of unusual locations that eventually resulted in a series of papers during a second tour with the U.S. Geological Survey in 1947 and 1948. There were papers with Hendricks and Nelson in 1946 on a portable differential thermal analysis unit for bauxite exploration, with Bergquist on aluminous lateritic soil of the Dominican Republic in 1947, and with Bridge in 1948 on the bauxite of Babelthuap Island in the Palau Group of islands.

Sam rejoined the University of Minnesota in 1948 and became Professor and Director of the Rock Analysis Laboratory the following year, a position he was to hold until his departure in 1959 (and was to receive the Minnesota Outstanding Achievement Award in 1985). Notable among his Ph.D. graduate students were Ralph Erickson who was the founding Branch Chief of the U.S. Geological Survey's Geochemical Exploration Branch, Ronald Burwash who became a professor at the University of Alberta, Harry Gehman who went to work in the oil industry, and Richard B. Taylor who became Chief of the Branch of Central Mineral Resources in the U.S. Geological Survey. Master's candidates included Gary Ernst, currently a Professor at Stanford University, and Zell Peterman a former Chief of the late Branch of Isotope Geology, U.S. Geological Survey, and a pioneer in strontium isotope geochemistry. During this period and in collaboration with Alfred Nier of the University of Minnesota, Sam organized a potassium-argon facility in the Department of Geology with Halfdon Baadsgaard (who also later became a professor at the University of Alberta). A number of important papers resulted from this collaboration.

Upon leaving the University of Minnesota, Goldich joined the U.S. Geological Survey a third

time and became the founding Branch Chief of the famous Branch of Isotope Geology in 1960, now defunct. Initially, the Branch was located at the old National Bureau of Standards site on Connecticut Avenue and Van Ness in Washington, D.C. (Now the site of the University of the District of Columbia). This location also allowed Goldich to make a close association with Bill Shields of the National Bureau of Standards (NBS, now called the National Institute of Standards and Technology) who was involved in using mass spectrometry for redetermining atomic weights. This association resulted in much upgrading of the instrumentation in the Branch plus the building of new equipment known as Shields Mass Spectrometers and led the late Paul Gast to say that Shields was the most valuable employee in the Branch of Isotope Geology and the U.S. Geological Survey didn't even have to pay him. The core of this Branch came from the old Nucleonics Group that had been headed by Frank Senftle. In addition to Senftle, there were Irving Friedman, Henry Faul, Lorin Stieff, Thomas Stern, and Meyer Rubin, among others. Stieff shortly left to pursue his interest in world peace. Faul and Goldich had a falling out and Faul eventually left for the University of Pennsylvania. Quickly added were Ron Kistler (who was soon to return to the U.S. Geological Survey in Menlo Park, California), Carl Hedge, Edward Catanzaro, and Bruce Doe. Catanzaro soon left to join Shields at the NBS. The NBS site had to be abandoned because of their move to Gaithersburg and the Assistant Chief Geology for the Central Region came up with a small building (Bldg. 21) at the former WW II munitions plant in Lakewood, Colorado, known as the Denver Federal Center. John Rosholt was already there, and Irving Friedman in 1963 was the first to move. John Stacey and Mitsunobu Tatsumoto were soon added and Bruce Doe moved there in 1963 followed by most of the others in 1964, including Robert Zartman and John Obradovich. During a period of years after this move, Senftle and Stern stayed in Washington, D.C., and joined other groups. Meyer Rubin was to remain there in the Branch with his carbon-14 operation. A popular way for the Branch of Isotope Geology to acquire researchers was from other branches. Zell Peterman, for example, came from a branch called Geochemical Census (and, for example, later in Menlo Park, Marvin Lanphere from the Branch of Alaskan Geology, and Brent Dalrymple from the Branch of Theoretical Geophysics). [History of the Branch of Isotope Geology after Sam ceased being Branch Chief in 1964 is not covered here.]

Doe, a Post-doctoral Fellow at the Geophysical Laboratory, was hired under an agreement that the

U.S. Geological Survey would acquire a 12-inch Shields solid-source mass spectrometer. After that, however, most equipment was obtained as a result of cooperation with other organizations. Stieff, for example, arranged an investigation of uranium series disequilibrium in soils that freed up money for a second 12-inch Shields mass spectrometer and the building of a clean laboratory for isotopic investigations in Denver. A program with Saudi Arabia freed up money for a 6-inch Shields solid-source mass spectrometer. Money was obtained from the Japan-U.S. Scientific Cooperation Program for an argon mass-spectrometer (for an entertaining account of the argon mass spectrometer, you are referred to Glynn's book "The Road to Jaramillo").

After his tour as Chief of the Branch of Isotope Geology, Goldich was to leave the U.S. Geological Survey again and from 1964-1965 joined Pennsylvania State University as Professor of Geology and Geochemistry and Director of the Mineral Constitution Laboratories, for which he was to hire his former associate Oliver Ingamells. The State University of New York began upgrading their faculty and Sam moved to the State University of New York at Stony Brook as Professor of Geology from 1965 to 1968 at which he oversaw the building of another isotope laboratory and hired Gil Hanson who became a professor there. Restless, he moved to Northern Illinois University in 1968 as Professor of Geology until his retirement in 1977 as emeritus and where he organized yet a fourth isotope geology laboratory. He was to move to Denver in his retirement and became emeritus at the Colorado School of Mines. Sam was a fellow of the American Geophysical Union, Mineralogical Society of America, and Geological Society of America.

No discussion of Sam would be complete without some mention of his famous personality. Although Sam could be very generous, he was prone to giving unsolicited good advice or opinions. This advice or opinions was often given in a tone that the recipient would take as criticism or, even, condemnation. Perhaps all those who were close to Sam, and even many more distant, experienced this at some time or other. He was prone to allergies which did not improve his disposition. I recall once in a class when he repeatedly asked some question in an increasingly agitated and loud voice punctuated by his blowing his nose as one student after another he called upon couldn't answer it. He finally said with a cute smile, "This class sure is stupid when I don't feel good." I recall thinking he didn't like me when I was an undergraduate at the University of Minnesota. I had

stayed on for a fifth year to get a bachelors degree in geological engineering but decided to go on and get a master's degree somewhere else as well. I went in to Sam to tell him this and I was going to ask him not to prejudice others that I would ask to write letters of reference for me. I only got out that I was thinking of going somewhere for a master degree when he interrupted that he thought that was a great idea and he could get me a good deal at Missouri School of Mines. He added that I would never regret it. So I decided to leave it at that, and he was right, I never did regret it. Later when I mentioned I wanted to go on for a Ph.D., he suggested I apply to Caltech and that he would have a place for me in the isotope lab when I flunked out. Well, I did apply and was accepted, but, fortunately, never flunked out. Once I told Dick Taylor about my confusion concerning the unexpected result over the master's degree proposal, and he replied, that Sam was hard on me because he thought I had potential. I had noticed that with certain students of little accomplishment he would talk about fishing, hunting, movies, and the like, but that he eventually even wrote papers with some of the people he was hardest on. However, he left an ill will with many which probably accounts for this remarkable scientist not winning more honors than he did. But there were a lot of us that learned to overcome Sam's outbursts and to regard him as a friend and wonderful scientist.

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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. The out-going, senior member of the Board of Directors shall act as liaison between the Board and the Committee for a period of one year.
- 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 medalist, 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 John C. Green

2001 John S. Klasner

GOLDICH MEDAL COMMITTEE

Mark Smyk (2001)

Ontario Geological Survey, Thunder Bay

Rod Johnson (2002)

Rod Johnson and Associates, Negaunee, Michigan

Frank Luther (2003)

University of Wisconsin, Whitewater

James D. Miller, Jr., as out-going senior member of Institute Board of Directors, is liaison between Goldich Medal Committee and the Board through the 2001 meeting.

CITATION FOR JOHN S. KLASNER 2001 GOLDICH AWARD RECIPIENT

It is my distinct honor and privilege to present this citation for John Klasner, the 22nd recipient of the Goldich Award. John was born and raised in the Upper Peninsula. He received his Bachelor's degree in 1957 from Michigan State. His first professional job was with INCO in the bush of northern Ontario in the summer of 1957. From 1958 to 1962, John worked for Geophysical Services International reducing seismic data for petroleum exploration in New Mexico, Texas, Wyoming, and then overseas in Libya and Muscat. He returned to Michigan State in 1962 and earned a Master's degree in geophysics in 1964. His thesis, mapping a bedrock valley by gravity methods was sponsored by the Groundwater Branch of the U.S.G.S. For the next five years, John worked for the Standard Oil Company of California as an exploration geophysicist stationed mainly in Anchorage, Alaska. He worked in the Cook Inlet area, and while in Anchorage, he met and married his wife, Gretchen, who also happens to be from the U.P. of Michigan. He worked in California from 1967 to 1969, and was then transferred back to Alaska in 1969 to work on the North Slope oil project.

In the fall of 1969, he left Standard Oil to work on a Ph.D. at Michigan Tech., under Jo Kalliokoski. His dissertation was on the structure and metamorphism in the western Marquette range. I believe that John's thesis was the first study to show that the Early Proterozoic rocks are detached from the Archean in the area, suggesting large-scale horizontal tectonics. Upon completion of his Ph.D. in 1972, John joined the faculty at Western Illinois University, where he taught for 27 years. He resumed his contact with the U.S.G.S. spending summers mapping in northern Michigan. John as applied his knowledge of geophysics and structural geology to solving problems in the Precambrian of a number of areas including the Marquette range, the Gogebic range, the Felch trough, several areas in Wisconsin and in the Trans-Hudson Orogeny. He has done a broader range of structural studies in the Lake Superior region than anyone I know. He has a long list of publications (49) resulting from his work, in addition to the teaching and administrative load at an undergraduate university. He received the highest awards offered by Western Illinois University for his teaching and research. An indication of the esteem with which he was held at Western is shown by his being named Director of their Honors Program from 1994-1998. He introduced many students to the mysteries of the Precambrian by leading a field trip to the area every year. Especially important, I think, has been his role of introducing undergraduate students to professional activities by supervising fourteen Senior theses and six Honors theses during his years of teaching at Western.

I have had the privilege of working directly with John since the mid-1980s, doing field work in Wisconsin and northern Michigan. During this time John has been the mentor for a number of NAGGED/USES Summer trainees and volunteers. I have found John to be an exceptionally dedicated teacher of young geologists, as well as being a very competent geologist himself, a very good woodsman, and a pleasant fellow to work with. Therefore, it is with great pleasure that I present the 2001 recipient of the Goldich Award for "Outstanding Contributions To The Geology Of The Lake Superior Region", John S. Klasner.

Gene L. LaBerge

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 substantial contributions made to the 1996 Institute meeting in his name. "Ned" Eisenbrey 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.

Successful applicants will receive their awards during the meeting.

<u>INSTITUTE ON LAKE SUPERIOR GEOLOGY</u>	
	
<i>Eisenbrey Student Travel Award Application</i>	
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 in the amount of 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.

STUDENT PAPER AWARDS COMMITTEE

Dave Meineke - Committee Chair

Meriden Engineering LLC

Anne Argast

Indiana University - Purdue University Fort Wayne

Thomas J. Evans

Wisconsin Geological and Natural History Survey

Steve Kircher

Nicolet Minerals

MEMBERSHIP CRITERIA
FOR THE INSTITUTE ON LAKE SUPERIOR GEOLOGY

Approved May 8, 1997

- A. Membership in the Institute on Lake Superior Geology requires either participation in Institute activities, or an indication on a regular basis of interest in the Institute. Those individuals registering for an annual meeting will remain as members for 4 years unless: 1) they indicate no further interest in the Institute by responding negatively to the statement on meeting circulars "Remove my name from the mailing list"; or 2) two successive mailings in different years are returned by the postal service as address unknown.
- B. Those individuals who have not registered for an annual meeting in the past 4 years must indicate an interest in the Institute by postal, electronic, or verbal correspondence with the Secretary-Treasurer at least once every two years. Such individuals will be removed from the membership if they indicate no further interest in the Institute or two successive mailing in different years are returned by the postal service as address unknown.
- C. The Secretary-Treasurer will maintain a list of current members. The list will include the date of the beginning of continuous membership, dates of returned mail, dates of last contact (expression of interest), and the date membership expires, barring a change of status initiated by the member. Those individuals who have become members of ILSG by Section B will have an expiration date listed at 2 years from the upcoming meeting. For example, a member who expresses interest in September of 1997 (the next annual meeting is May, 1998) will have an expiration date of May, 2000, unless the member contacts the Secretary-Treasurer or attends an annual meeting.
- D. "Member for Life" status is granted to individuals who have been (nearly) continuous participants of the ILSG meetings for 15 years, Goldich Medal recipients, or those who have served as meeting chairs. This status will be further maintained unless the individuals indicate no further interest in the Institute, or 4 mailings in different years are returned by the postal service as address unknown, or they are deceased.
- E. All members will be mailed the First Circular for the Annual Meeting and the ILSG Newsletter. The Chair of the annual meeting may opt to send the first circular to additional individuals. All returned mail should be reported to the Secretary-Treasurer.
- F. The Secretary-Treasurer can designate any individual who is on the ILSG membership list (mailing list) as of January 1, 1997 as a member for life based on participation in ILSG activities.
- G. Members are strongly encourage to send address corrections to the Secretary-Treasurer to avoid unintentional lapse of membership.

2001 BOARD OF DIRECTORS

(Board membership through the close of the meeting year shown)

Michael G. Mudrey, Jr., General Chairman (2004)

Bruce A. Brown, Co-chair

Wisconsin Geological and Natural History Survey

Stephen A. Kissin (2003)

Lakehead University

Theodore J. Bornhorst (2002)

Michigan Technological University

James D. Miller, Jr. (2001) Goldich Liaison

Minnesota Geological Survey

Mark A. Jirsa - Executive Secretary (2002)

Minnesota Geological Survey

2001 LOCAL PLANNING COMMITTEE

Michael G. Mudrey, Jr. - Co-chair

Bruce A. Brown - Co-chair

Robert H. Dott, Jr. - Program Co-chair

L. Gordon Medaris, Jr. - Program Co-chair

Kathleen M. Zwettler - Meeting Coordinator

Assistance to the local committee was provided by the following individuals from the Wisconsin Geological and Natural History Survey:

James M. Robertson

Director and State Geologist - Wisconsin Geological and Natural History Survey

Virginia Trapino

Office Support

Mindy James

Publication Preparation

Susan Hunt

Graphic Arts

Michael L. Czechanski

Program and Technical Assistance

2001 SESSION CHAIRS

(In order of appearance)

James M. Robertson - *Geologic Overview of Southern Wisconsin*
Wisconsin Geological and Natural History Survey

D.L. Daniels - *Geophysical Overview and Earliest Archean Evolution*
U.S. Geological Survey

William F. Cannon - *Geology and Hydrogeology of Arsenic in Domestic and Public Water Supplies*
U.S. Geological Survey

Michael D. Lemcke - *Geology and Hydrogeology of Arsenic in Domestic and Public Water Supplies*
Wisconsin Department of Natural Resources

Suzanne W. Nicholson - *General Geology*
U.S. Geological Survey

Dean Rossell - *Developments in Understanding Keweenaw Geology*
Kennecott Exploration Company

D.K. Holm - *Thermo-Tectonic History of 1800 to 1200 Ma post-Penokean to Pre-Keweenaw Rocks*
Bowling Green State University

D.A. Schneider - *Thermo-Tectonic History of 1800 to 1200 Ma post-Penokean to Pre-Keweenaw Rocks*
Syracuse University

Eric Jerde - *Developments in Understanding Archean Geology and Ore Deposits*
Morehead State University

2001 BANQUET SPEAKER

Thomas C. Hunt
University of Wisconsin - Platteville

A Practical Exercise in Metallic Mine Reclamation - Ladysmith, Wisconsin

**REPORT ON THE 46TH ANNUAL MEETING
OF THE INSTITUTE ON LAKE SUPERIOR GEOLOGY
*Thunder Bay, Ontario***

The 46th Annual Meeting of the Institute on Lake Superior Geology was held in Thunder Bay, Ontario, May 8-13, 2000, at Lakehead University. The meeting was sponsored by the Department of Geology, Lakehead University, with the assistance of the Ministry of Northern Development and Mines, Thunder Bay office. The meeting was co-chaired by Stephen A. Kissin and Philip W. Fralick. The meeting was attended by approximately 200 geoscientists from the United States and Canada. The meeting consisted of two days of technical sessions, with welcoming reception and annual banquet, and after six field trips before and after the technical sessions.

The Proceedings Volume 46 was published in two parts. Part 1 - Program and Abstracts was edited by Stephen A. Kissin. There were 41 published abstracts for the 23 oral and 18 poster presentations given in the technical sessions. Part 2 - Field Trips was edited by Philip W. Fralick. There were six field trips, one before and after the technical sessions; all were described by the respective leaders in Part 2 of the Proceedings.

The field trips were as follows:

- 1) Mesoproterozoic Sibley Group was lead by Philip Fralick and Mark Smyk. This was a two day trip.
- 2) Lac des Iles Mine was lead by Moe Lavigne. The trip was run before and after the technical sessions.
- 3) Geoarcheology of the Thunder Bay Area was lead by Brian Phillips, Scott Hamilton, Joe Stewart, Pat Julig, and Bill Ross.
- 4) Paleoproterozoic Gunflint Formation was lead by Peir Pufahl and Philip Fralick.
- 5) Quaternary Geology, Shebandowan Belt was lead by Andy Bajc.
- 6) Steeprock-Finlayson-Lumby Belts, a two day trip was lead by Denver Stone, Kirsty Tomlinson, Ray Bernatchez and Philip Fralick.

The annual banquet was held in the Residence Dining Room at Lakehead University. The dinner speaker was Bruce Simonson of Oberlin College whose talk "Depositional Settings and Early Diagenesis of Large Precambrian Iron-Formations" was enthusiastically received. The 2000 Goldich Medal was awarded to John C. Green for his contributions to the geology of the North Shore Volcanic Group.

The technical sessions included seven invited papers on the Canadian side of Lake Superior: M.M. Kehlenbeck "A Review of Structures in Rocks of Quetico Subprovince and Adjacent Terranes", D.W. Davis "Western Superior Province: Geochronologic Aspects", K. Tomlinson "Western Superior Province: Sedimentological Aspects", M.J. Lavigne "The Lac des Iles Mine, Northwestern Ontario", P.W. Fralick "Western Superior Province: Proterozoic Sediments", and S.A. Kissin "Vein-type Deposits of the Thunder Bay Area". Student awards were given to Neil Pettigrew (University of Ottawa) for his oral presentation on the Samuels Lake intrusion, Ontario and to K.F. Beaster and J.D. Kohn (University of Wisconsin-Eau Claire) for their poster presentation on the Hinckley Sandstone of Minnesota. The Eisenbrey Student Travel Award was distributed among eight student presenters of oral and poster papers.

The Board of Directors of the Institute met for a brief business meeting on May 10. Michael Mudrey of the Wisconsin Geological and Natural History Survey agreed to host the 2001 meeting at Madison, Wisconsin. The term of the Secretary-Treasurer, Mark Jirsa, expired at this meeting. He was nominated for an additional term as Secretary-Treasurer. There being no further nominations, he was acclaimed for an additional term.

We wish to thank all those who contributed to the success of the meeting. The field trip leaders who contributed to the guidebook in Part 2 and devoted time and energy to field trips merit our special thanks. The session chairs are thanked for their services as well as the awards committee. We are especially grateful to Mark Smyk and staff of the Ministry of Northern Development and Mines, Sam Spivak, Karen Farrier, Becky Rogola and France Lagroix of the Department of Geology for invaluable assistance. Finally we would like to thank all participants whose attendance made the meeting a financial success.

Stephen A. Kissin and Philip W. Fralick
Co-Chairs of the 46th Annual ILSG

CALENDAR OF EVENTS AND PROGRAM

WEDNESDAY MAY 9

8:00 a.m. **FIELD TRIP 1: Sedimentology, Tectonic and Metamorphic History of the Baraboo Interval:
New Evidence from Investigations in the Baraboo Range, Wisconsin**

L.Gordon Medaris, Jr. and Robert. H. Dott, Jr.
University of Wisconsin - Madison

6:00 p.m. **Return of Trip 1**

5:00 p.m. - 8:00 p.m. **Registration**

7:00 p.m. - 10:00 p.m. **Welcoming Reception, Cash bar and Poster Setup**

THURSDAY MAY 10

7:00 a.m. - 9:00 a.m. **REGISTRATION**

8:10 a.m. **INTRODUCTORY REMARKS**

M.G. Mudrey, Jr. Chairman
Wisconsin Geological and Natural History Survey

SESSION I: GEOLOGIC OVERVIEW OF SOUTHERN WISCONSIN

Session Chair: J.M. Robertson, *Director and State Geologist, Wisconsin Geological and
Natural History Survey*

8:20 a.m. **MICKELSON, D.M.** and Clayton, L., (*University of Wisconsin - Madison;
Wisconsin Geological & Natural History Survey*)

Recent Advances in Understanding the Glacial Record of Wisconsin

9:05 a.m. **BYERS, C.E.** (*University of Wisconsin - Madison*)

Overview of Paleozoic Geology in Southern Wisconsin

9:50 a.m. **MEDARIS, L.G., Jr.** (*University of Wisconsin - Madison*)

Precambrian Geology of S. Wisconsin: A Panorama from the Baraboo Range

10:35 a.m. **COFFEEBREAK AND POSTER SESSION**

SESSION II: GEOPHYSICAL OVERVIEW AND EARLIEST ARCHEAN EVOLUTION

Session Chair: D. Daniels, *U.S. Geological Survey*

10:55 a.m. **CHANDLER, Val W.** and **MUDREY, M.G., JR.**

Overview of Aeromagnetic Mapping: Minnesota (Chandler) and Wisconsin (Mudrey)

11:20 a.m. **CANNON, W.F.**, Daniels, David L., Snyder, Stephen L., and Nicholson, Suzanne W.

A Preliminary Interpretation of New Aeromagnetic and Gravity Data in Wisconsin

11:40 a.m. **VALLEY, J.W.**, Peck, W.H., King, E.M., Graham, C.M., and Wilde, S.A.

**The Cool Early Earth: Oxygen isotope Evidence for Continental Crust and Oceans on Earth at
4.4 Ga**

NOON

LUNCH BREAK

ILSG BOARD MEETING (*by invitation*)

POSTER SESSION

SESSION III: GEOLOGY AND HYDROGEOLOGY OF ARSENIC IN DOMESTIC AND PUBLIC WATER SUPPLIES

Session Chairs: W.F. Cannon (*U.S. Geological Survey*)
M.D. Lemcke (*Wisconsin Department of Natural Resources*)

- 1:30 p.m. **NORDSTROM, D. Kirk** (*U.S. Geological Survey*)
Overview of Arsenic Occurrences and Processes in Controlling Mobility in Groundwater
- 2:30 p.m. **MUDREY, M.G., Jr.**, Brown, B.A., Freiberg P.G., and Simo, J.A.
Mississippi Valley-Type Mineralization in the Fox River Valley, Eastern Wisconsin
- 2:45 p.m. **GOTKOWITZ, M.B.**, Schreiber, M.E., and Simo, J.A.
Contrasts in the Geologic and Hydrochemical Occurrences of Arsenic contamination of Groundwater in Eastern Wisconsin
- 3:05 p.m. **KANIVETSKY, Roman**
Hydrogeochemical Modeling of Arsenic in Minnesota Ground Water
- 3:25 p.m. **KOLKER, Allan**, Cannon, W.F., Haack, S.K., Westjohn, D.B. and Woodruff, L.G.
Hydrogeologic Setting of Elevated Arsenic in Southeastern Michigan
- 3:45 p.m. **COFFEE BREAK AND POSTER SESSION**

SESSION IV: GENERAL GEOLOGY

Session Chair: Suzanne W. Nicholson, *U.S. Geological Survey*

- 4:05 p.m. **WOODRUFF, L.G.**, Attig, J.W., and Cannon, W.F.
Geochemistry of Quaternary Deposits in North-central Wisconsin: Geochemical Exploration and Provenance Analysis
- 4:25 p.m. **FAUBLE, Philip**, and Lien, Jennifer
Some Observations from the Williams Quarry Exposure: Evidence of Debris Flow Deposits in the Parfeys Glen Formation?
- 4:45 p.m. **BOERBOOM, Terrence J.** and Jirsa, Mark A.
Stratigraphy of the Paleoproterozoic Denham Formation - a Continental Margin Assemblage of Basalt, Arkose, and Dolomite
- 6:00 p.m. **ICE BREAKER - MIXER**
Cash Bar
- 7:00 p.m. **ANNUAL BANQUET AND AWARD PRESENTATION**
- **Announcement of 48th Annual Meeting Location**
 - **Memorial on Samuel Stephen Goldich 1909 - 2000**
 - **2001 Goldich Award Presentation to John Klasner**
 - **Banquet Speaker: Thomas Hunt, University of Wisconsin Platteville**

***A Practical Exercise in Metallic Mine
Reclamation - Ladysmith, Wisconsin***

Participants who are not registered for the banquet are welcome to join for the speaker

FRIDAY MAY 11

8:10 a.m. *INTRODUCTORY REMARKS*

M.G. Mudrey, Jr. Chairman
Wisconsin Geological and Natural History Survey

SESSION V: *DEVELOPMENTS IN UNDERSTANDING KEWEENAWAN GEOLOGY*

Session Chair: Dean Rossell, *Kennecott Exploration Company*

8:20 a.m. **MILLER, James D., Jr.**

The Duluth Complex: What it Is, What it Ain't, and What We Still Don't Know

8:50 a.m. **GREEN, J.C.,** Davis, D.W., and Schmitz, M.D.

Three New Zircon Dates for the Midcontinent Rift, North Shore, Minnesota: More Data, More Questions

9:10 a.m. **ROGALA, B.,** and Fralick, P.W.

A Metamorphosed Evaporite Sequence from the Sibley Basin

SESSION VI: *THERMO-TECTONIC HISTORY OF 1800 TO 1200 MA POST-PENOKEAN TO PRE-KEWEENAWAN ROCKS IN THE MIDWEST*

Session Chairs: D.K. Holm, *Kent State University*
D.A. Schneider, *Syracuse University*

9:30 a.m. **HOLM, D.K.,** Van Schmus, W.R. and MacNeill, L.C.

Age of the Humboldt granite, northern Michigan: Implications for the origin of the Republic metamorphic node

9:50 a.m. **VAN SCHMUS, W.R.,** MacNeill, L.C., Holm, D.K., and Boerboom, T.J.

New U-Pb Ages from Minnesota, Michigan, and Wisconsin: Implications for Late Paleoproterozoic Crustal Stabilization

10:10 a.m. **COFFEEBREAK AND POSTER SESSION**

10:30 a.m. **SCHWEITZER, D.,** Holm, D., Van Schmus, W.R. and Boerboom, T.

Results of Igneous Thermometry and Barometry on the East-central Minnesota Batholith: Evidence for Post-emplacement Exhumation and Cooling

10:50 a.m. **NAYMARK, Alissa,** Singer, Brad, and Medaris, L.G., Jr., Recognition of Post-1630 Ma Fluid-driven Metamorphism in Baraboo Interval Quartzites by Means of Laser Probe $^{40}\text{Ar}/^{39}\text{Ar}$ Geochronology

11:10 a.m. **DAVIS, Peter B.,** Williams, Michael L., Bowring, Samuel A. and Ramezani, Jahan Middle Proterozoic Tectonic History of the Central Tusas Mountains, Northern New Mexico, and Comparison with the Baraboo Interval, Southern Lake Superior Region

11:30 a.m. **WILLIAMS, M.L.,** Jercinovic, M.J., and Karlstrom, K.E. Proterozoic Tectonic History of Southwestern North America: Insight from Microprobe Monazite Geochronology

11:50 a.m. **HOLM, D.,** Jercinovic, M.M., and Williams, M. Initial Results of In Situ electron Microprobe (EMP) Age Dating of Monazite from the Southern Lake Superior Region: Confirmation of Widespread Geon 17 Metamorphism

12:10 p.m. **SCHNEIDER, D.A.**, Holm, D.K., and Hamilton, M.A.
Directing Timing Constraints of Paleoproterozoic Metamorphism, Southern Lake Superior
Region: Results from Shrimp U-Pb Dating of Metamorphic Monazites

12:30 **LUNCH BREAK**

POSTERS removed after Lunch

SESSION VII: DEVELOPMENTS IN UNDERSTANDING ARCHEAN GEOLOGY AND ORE DEPOSITS

Session Chair: Eric Jerde, *Morehead State University*

- 2:00 p.m. **HUDAK, George J.**, Peterson, Dean M., and Morton, Ronald L.
New Volume Calculations for the Pyroclastic Eruptions Associated with the Sturgeon Lake
Caldera Complex, Northwestern Ontario: Implications for the Scale of Archean Volcanic
Processes
- 2:20 p.m. **PETERSON, D.M.**, Gallup, C., Jirsa, M.A. and Davis, D.W.
Correlation of Archean Assemblages Across the U.S.-Canadian Border: Phase I Geochronology
- 2:40 p.m. **JIRSA, Mark A.** and Chandler, Val W.
Geophysical Answers to Geologic Queries in the Superior Province of Northern Minnesota
- 3:00 p.m. **SMYK, Mark C.**, Mason, John K., Schnieders, Bernie R., and Stott, Greg M.
A Synopsis of Archean and Proterozoic Platinum Group Element Mineralization in the Thunder
Bay District, Ontario
- 3:20 p.m. **COFFEEBREAK**

SESSION VIII: GEOLOGIC SETTINGS OF WEEKEND FIELD TRIPS

- 3:40 p.m. **MUDREY, M.G., Jr.**, Hunt, T.C., and Czechanski, M.L.
Overview of Field Trip 2: Upper Mississippi Valley Zinc-Lead District
- 4:00 p.m. **BROWN, B.A.**, Luther, F.R., Courter, S.M., Schmitt, J.W., and Lien, J.
Field Trip 3: Economic Geology of the Baraboo and Waterloo Quartzites
- 5:00 p.m. **SINGER, Brad** (*Department of Geology and Geophysics*)
Tour of Weeks Hall, University of Wisconsin and Weeks End Refreshment Seminar
(*Transportation provided*)

SATURDAY MAY 12

- 8:00 a.m. **FIELD TRIP 2: Upper Mississippi Valley Zinc-Lead District**
M.G. Mudrey, Jr. and Thomas C. Hunt
Wisconsin Geological and Natural History Survey and University of Wisconsin - Platteville
- 8:00 a.m. **FIELD TRIP 3: Industrial Mineral and Aggregate Resources of the Baraboo Interval Quartzites**
Brown, B.A., Luther, F.R., Courter, S.M., Schmitt, J.W., and Lien, J.
*Wisconsin Geological and Natural History Survey, University of Wisconsin - Whitewater, Mathy
Construction, Kraemer Company*
- 6:00 p.m. **Return of Field Trips**

POSTER PRESENTATIONS

BESKAR, Shawn

The Blake Gabbro: A taxitic-textured gabbro sill south of Thunder Bay, Ontario

BIHARI, D.B. and Kissin, S.A.

Alteration and Pge-au Mineralization in the North Roby Zone, Lac Des Iles Mine, Northwestern Ontario

BOERBOOM, Terrence J.

Redefined Volcanic and Sedimentary Stratigraphy of the Northern St. Croix Horst in Pine County, Minnesota, and the Application of Arcview to Geologic Mapping

BROWN, B.A. and Czechanski, M.L.

GIS Applications for Resource Inventory and Land-use Planning in Wisconsin

BUCHHOLZ, Thomas W., Falster, Alexander U., and Simmons, Wm. B.

Recent Developments in the Mineralogy of the Nine Mile Pluton, Wausau Complex

CANNON, W.F. and Woodruff, L.G.

Regional Arsenic Anomalies Shown by NURE Stream Sediment and Hydrogeochemical Data in Northern Wisconsin and Michigan

CHANDLER, Val W. and Morey, G.B.

Paleomagnetic Study of Paleoproterozoic Rocks in the Animikie Group, Northern Minnesota

DAHL, D.

Structure, Stratigraphy and Punctuated Evolution of Minnesota's Mineral Exploration Archives

DANIELS, David L., Nicholson, Suzanne W., Cannon, William F., and Kucks, Robert P.

New Aeromagnetic Map of Wisconsin Examined by Regional Context

Jerde, Eric A., **SALVATO, Daniel J.**, Thole, Jeff and Wirth, Karl R.

The Early Gabbroic Series of the Midcontinent Rift System: Continued Assessment of Magmatic Origins

JOHNSON, Dave

Distribution of Arsenic in Wisconsin Groundwater

JOHNSON, J.R. and Kissin, S.A.

Fluid Inclusion Evidence for a Role for Hydrothermal Activity in the Roby Zone, Lac Des Iles Mine, Northwestern Ontario

KELLY, Colleen, and Kean, William F.

Rock Magnetic Studies of Phyllitic Zones from the Baraboo Syncline, Wisconsin

KNOBELOCH, Lynda, Warzecha, Charles. and Nelson, Shelli

Health Surveillance in a Community Affected by Arsenic-Contaminated Water

LARSON, Phillip C.

Potential for Copper Mineralization in the Animikie Group, Minnesota

LIVELY, Richard and Morey, G.B.

Contributions to the Cultural Geography of the West Mesabi Range, Northern Minnesota

- MILLER, J.D., Jr.**, Wahl, T.E., Green, J.C., Chandler, V.W., Severson, M.A., and Peterson, D.E.
Digital Geologic Map of Northeastern Minnesota and Associated Databases in GEMS - a Modified
Arcview Format
- MUDREY, M.G., Jr.**, and Brown, B.A.
Structure of the Buried Precambrian Basement in Southwest Wisconsin and Its Influence on Regional
Paleozoic Geology and Zinc-Lead Mineralization
- MUDREY, M.G., Jr.**, Brown, B.A. and Daniels, Daniels L.
Preliminary Analysis of Aeromagnetic Data in Southern Wisconsin: The Role of Precambrian
Basement in Paleozoic Evolution
- NEMITZ, Michael B.** and Larson, Phillip C.
Mineralogical Variations in Iron-formation in the Thermal Metamorphic Aureole of a Diabase Dike
- NEWKIRK, Trent T.**, Hudak, George J., and Hauck, Steven A.
Preliminary Lava Flow Morphology Studies at the Five Mile Lake Vms Prospect, Archean Vermilion
District, Ne Minnesota: Implications for Volcanic Processes, Volcanic Paleoenvironments, and VMS
Exploration
- NICHOLSON, S.W.**, Boerboom, T., Cannon, W.F., Wirth, K., and Isachsen, C.E.
A New Look at the 1.1 Ga Chengwatana Volcanics in the St. Croix Horst, Minnesota and Wisconsin
- ODETTE, Jason D.**, Hudak, George J., Suszek, Thomas, and Hauck, Steven A.
Preliminary Evaluation of Hydrothermal Alteration Mineral Assemblages and Their Relationship to
VMS-style Mineralization in the Five Mile Lake Area of the Archean Vermilion Greenstone Belt,
Northeastern Minnesota
- PETERSON, Dean M.**, Gallup, Christina, Jirsa, Mark A. and Davis, Donald W.
Correlation of Archean Assemblages Across the U.S.-Canadian Border: Phase I Geochronology
- PEYCHAL, C.**, Kean, W.F., and Schaper, D.
Magnetic Survey Near Waterloo Wisconsin
- PHILLIPS, Erin H.**, Wirth, Karl R., Vervoort, J.D. Gehrels, G.E.
Nd and U-Pb Isotope Studies of the Syenitic Aurora Sill, Mesabi Range, Minnesota
- REID, Daniel D.**
Freeze/Thaw Testing of Carbonate Aggregate Sources in Wisconsin - a Status Report
- SANDLAND, Travis O.**, Wirth, Karl R., Vervoort, Jeff D., Gehrels, George E., Kennedy, Bryan
C. and Harpp, Karen S.
Roles of Fractional Crystallization and Assimilation in the Production of Midcontinent Rift Grano-
phyres
- SMYK, Mark C.**, Stewart, Jennifer and O'Brien, Mark S.
Platinum Group Element Exploration in Northwestern Ontario
- SNYDER, Stephen L.**, Ervin, C.Patrick, Geister, Daniel W., and Daniels, David L.
A New Gravity Map of Wisconsin
- SOOFI, M.A.** and King, S.D.
Post-rift Evolution of the Midcontinent Rift System: Some Numerical Experiments
- Weissbach, Annette E., **HEINEN Elizabeth M.**, and Lauridsen, Keld B.
A Study of Well Construction for Arsenic Contamination in Northeast Wisconsin

Industry and Informational Displays

CRONK, William J.

Layne Northwest, W229 N5005 DuPlainville Rd, Pewaukee, WI 53072. Phone (262)-246-4646

KIRCHER, Steve

Crandon Mine Development, Nicolet Minerals, 7 N. Brown St, 3rd Floor, Rhineland, WI 54501.
Phone (715)365-1450 (Rhineland office), (715)478-1516 (Crandon office)

STEWART, Jennifer

Ontario Geological Survey Resident Geologist Program, Northwestern Ontario District, Suite B002,
475 South James Street, Thunder Bay ON, P7E 6E3. Phone (807) 475-1108

SUNDEEN, S. Paul

Michigan Department of Environmental Quality, Geological Survey Division, 735 E. Hazel Street,
P.O. Box 30256, Lansing, MI 48909. Phone (517) 334-6959.

The Blake Gabbro: A taxitic-textured gabbro sill south of Thunder Bay, Ontario.

Shawn Beskar - University of St. Thomas

South of Thunder Bay, Ontario, plutonic and hypabyssal rocks associated with the Keweenawan Rift (1109 Ma to 1086 Ma) intrude sedimentary rocks of the Lower Proterozoic (1.9 Ga) Animikie Group. Prior to the discovery of the Blake Gabbro, the igneous terrane south of Thunder Bay was thought to have been comprised of five distinct intrusions (Lightfoot and Lavigne, 1995): (1) Logan Sills; (2) Arrow River Dikes; (3) Pigeon River Dikes; (4) Crystal Lake Gabbro; (5) Pine River - Mount Molly Intrusion.

Discovered in 1995, the Blake Gabbro is situated south of Thunder Bay within Blake Township, some 60 km north of the Duluth Complex. The region is characterized by northeast trending diabase-capped ridges and deeply eroded valleys. Positioned beneath a sequence of flat lying Logan Sills, the Blake Gabbro intrudes the argillites of the Rove Formation (Animikie Group). Since 1995, diamond drill cores that intersect the Blake Gabbro have been recovered and logged. From these cores it has been determined that the Blake Gabbro is a northeast trending, sub-horizontal sill of limited plan width but unknown strike length. The maximum thickness intersected by holes drilled thus far is 131 m. The sill thins to less than 20 m at its margins, some 300 m from the center of the body.

Samples of the Blake Gabbro have been taken from the diamond drill cores for petrologic study. Initial studies indicate that the Blake Gabbro is a taxitic-textured sulphide-bearing sill. Plagioclase and pyroxene are present in roughly equal quantities. Elongate, cumulus plagioclase grains of variable size are enclosed by optically continuous intercumulus pyroxene. Initial analyses of plagioclase yield compositions ranging from An₇₂ to An₈₃. Minor amounts of olivine and biotite are present. Sulphide minerals consist of pyrrhotite and chalcopyrite. Preliminary whole-rock geochemical data obtained through XRF spectroscopy is presented in Table 1.

The significance of the Blake Gabbro is realized upon comparison with the igneous terrane of Noril'sk, Siberia. The region south of Thunder Bay is thought to be equivalent in many respects to the geologic setting of the Noril'sk region and as such, may host large magmatic sulphide deposits (Lightfoot and Lavigne, 1995). The Keweenawan Osler Group Volcanic rocks are similar in composition to the Nadezhdinsky Formation lavas at Noril'sk. Both exhibit large degrees of crustal contamination (as evidenced by their high silica content and La/Sm ratio) and are depleted in nickel and copper. At Noril'sk, chonoliths (subvolcanic tube-like magma channels) containing mineralized picrites and gabbros served as feeders to the overlying sequence of flood basalt. It is thought that the Blake Gabbro may represent such a conduit. Chalcophile elements (nickel, copper and platinum group metals) missing from the associated Osler Group Volcanic sequence may reside within the Blake Gabbro, although the preliminary geochemical data presented seems to suggest otherwise.

REFERENCES

Lightfoot, P.C. and Lavigne, Jr., M.J. 1995. Nickel, copper, and platinum group element mineralization in Keweenawan intrusive rocks: new targets in the Keweenawan of the Thunder Bay region, northwestern Ontario: Ontario Geological Survey, Open File Report 5928, 32p.

Table 1. Preliminary whole-rock geochemistry

Major element data presented as weight per cent

Trace element data presented as parts per million

	BP98.1-1	BP99.1-2	BP99.2-1	BP99.3-2	BP99.3-3
SiO ₂	51.42	49.29	48.54	52.00	51.18
TiO ₂	3.38	1.43	1.27	2.95	3.48
Al ₂ O ₃	13.84	18.52	15.18	13.65	13.97
Fe ₂ O ₃	17.09	10.91	11.14	16.15	16.54
MnO	0.17	0.14	0.14	0.15	0.16
MgO	4.44	6.72	10.16	4.62	4.92
CaO	6.76	10.85	9.11	6.68	6.99
Na ₂ O	2.97	2.81	1.58	2.67	2.70
K ₂ O	1.35	0.66	0.61	1.38	1.33
P ₂ O ₅	0.59	0.25	0.18	0.44	0.48
Total	102.01	101.58	97.91	100.69	101.75
Sc	23.5	25.6	25.2	25.8	26
V	337.5	224	200.9	343.9	396.8
Cr	51.8	157.1	104.8	63.1	48.9
Co	46.1	46.7	58	47.5	45.9
Ni	67	121.1	207	79.2	74.5
Zn	162.5	82.9	90.6	172.9	144.9
Ga	25.6	20.9	19.5	23.9	24.1
Rb	54.9	23.2	29.3	61.3	60.8
Sr	425	306.6	348.8	447.4	501.8
Y	42.4	23.5	20.4	36.2	36
Zr	277.8	101.7	87.3	243.6	233.5
Nb	30.8	9.7	9.5	27.4	28.9
Ba	337.7	167.4	189.3	390.9	442.8
La	32.4	6.6	4.2	32.3	24.8
Ce	79.5	26.6	25.6	77.3	68.7
Pb	7.5	3.9	3	10.1	6.7

ALTERATION AND PGE-AU MINERALIZATION IN THE NORTH ROBY ZONE, LAC DES ILES MINE, NORTHWESTERN ONTARIO

BIHARI, D.B. and KISSIN, S.A., Department of Geology, Lakehead University, Thunder Bay, ON, P7B 5E1, stephen.kissin@lakeheadu.ca

The Lac des Iles Complex appears as a linear zone of mafic plutons that trend east to northeast and extends from Lake Nipigon to Atikokan in northwestern Ontario (Sutcliffe, 1986). The complex is situated in Archean granitoids that consist of gneissic tonalites, medium-grained hornblende diorites and quartz diorites. The Lac des Iles Complex occurs in a circular outcrop fashion that is approximately 30 km in diameter and is the largest of a series of mafic to ultramafic intrusions (Sutcliffe, 1986). The Roby Zone was the initial site of mining at the Lac des Iles Mine. The North Roby Zone is its narrow northward extension.

The North Roby Zone contains a narrow strip (<50 m) of anomalously high PGE and Au values associated with sparse sulfides called "noseum ore". Five stripped outcrops approximately 50 x 10 m were studied in the North Roby Zone. Alteration of primary pyroxene to talc and pink coloration of recessively weathered plagioclase is strongly suggestive of hydrothermal alteration.

The five stripped outcrops reveal a northeasterly striking, steeply dipping sequence of leucogabbro, varitextured gabbro, pyroxenite and east gabbro. A total of 32 hand samples were collected and studied in thin section. From these 21 were selected for whole-rock and trace element analysis in order to compare chemistry of altered and unaltered samples.

Hydrothermal alteration appears to have affected the primary ortho- and clinopyroxenes of the host rocks, progressively converting them to talc. Other petrographic indications are obscure, as regional metamorphism has overprinted the Lac des Iles Complex and its mineralized rocks.

The grade of metamorphism is the albite-epidote subfacies of greenschist facies as evidence by incipient breakdown of plagioclase to sericite and clinozoisite, chloritization of pyroxenes and formation of tremolite-actinolite, as well as minor metamorphic albite. Chlorite coronas surround mafic minerals, and develops decussate assemblages of chlorite and tremolite-actinolite. Minor penetrative deformation is evident in undulatory extinction in plagioclase and development of weak schistosity.

The development chlorite coronas and general overprinting of mafic minerals by chlorite and sericitization of plagioclase are significant in distinguishing hydrothermal alteration from subsequent regional metamorphism.

Analysis did not generally reveal striking compositional variations in the host rocks; however, more detailed analysis did show chemical effects of alteration. Chondrite-normalized REE plots revealed that all REEs were depleted relative to unaltered rocks; however, in most altered leucogabbro and varitextured gabbro, minor to insignificant depletion of Eu relative to other REEs produced an apparent positive Eu anomaly in the plots.

Other chemical changes, because of their subtle expression and obscurity owing the problem of closure, were examined by use of Pearce Element Ratios. Most notable was Na-depletion due to alteration, which can be distinguished from igneous fractionation effects in plagioclase.

Sutcliffe, R.H., 1989. Magma Mixing in Late Archean Tonalitic and Mafic Rocks of the Lac des Iles Area, Western Superior Province. *Precambrian Research*, vol. 44, pp.81-101.

REDEFINED VOLCANIC AND SEDIMENTARY STRATIGRAPHY OF THE NORTHERN ST. CROIX HORST IN PINE COUNTY, MINNESOTA, AND THE APPLICATION OF ARCVIEW TO GEOLOGIC MAPPING

BOERBOOM, Terrence J.

(Minnesota Geological Survey, boerb001@umn.edu)

Pine County, Minnesota, located on the northwestern margin of the St. Croix horst (Fig. 1), contains bedrock that ranges from Archean to Paleozoic in age; however, most of the county is underlain by rocks of the Midcontinent rift (Fig. 2). The southeastern half of the county is underlain by mafic volcanic rocks of the St. Croix horst, late rift-filling sedimentary rocks (Hinckley Sandstone and Fond du Lac Formation) underlie the central part of the county, and the far northwestern corner is made up of Archean and Paleoproterozoic rocks (see Boerboom, this volume). This county was recently remapped by the Minnesota Geological Survey (MGS)¹, but due to generally poor outcrop, the mapping relied heavily on geophysical and drill hole data. ArcView GIS software proved useful in manipulating and integrating these data, particularly the 4000 water wells contained in the MGS County Well Index database.

This presentation is intended to demonstrate the usefulness of ArcView software in map construction, and also to show the results of our mapping efforts in Pine County. Other Arc files to be demonstrated include maps of depth to bedrock, bedrock topography, and surficial geology.

Craddock (1972) provides a review of the history of investigations in Pine County and environs, but some of the notable early accounts of the bedrock geology in Pine County are by Upham (1888) and Hall (1901); Grout (1910) described the occurrence of copper mineralization in Pine County. The most recent published geologic map to cover Pine County is 1:250,000 scale (Morey and others, 1981). Our latest mapping coincides with other mapping projects in adjacent Wisconsin (Wirth and others, 1998, Cannon and others, 2001; Nicholson and others, 2001).

Geologists on both sides of the border benefited greatly from the recent acquisition of high-resolution aeromagnetic data in Wisconsin by the U.S.G.S., as summarized by Cannon and others (2001).

The St. Croix horst, part of the Mesoproterozoic Midcontinent rift system, is comprised of subaerial mafic volcanic rocks that have traditionally been lumped together as the Chengwatana volcanic group. Based on our work and that of the U.S.G.S., the term "Chengwatana" is now restricted only to those volcanic rocks that lie between the Douglas and Pine Faults (Fig. 2). The demarcation of Keweenaw sedimentary vs. volcanic rocks (i.e. the Douglas Fault) is well-defined on the basis of water well information. The Pine Fault (Fig. 2) lies inboard of and parallel to the Douglas Fault, and as summarized by Cannon and others (2001), may have been a bounding fault that controlled the distribution of graben-fill volcanic rocks.

Hall (1901) first applied the term "Chengwatana Series" to a series of steeply dipping basalt flows and interflow conglomerates exposed along the Snake River near Pine City, Minnesota. According to Hall: "*The flood of 1898, which tore away the dam at the foot of Cross Lake and poured down the [Snake] river a vast volume of water, cleaned out in an admirable manner for examination the channel of the stream for several miles.*" In this stretch of outcrop, Hall recognized 65 steeply dipping lava flows and five interflow conglomerates. Our remapping of this now less well-exposed sequence identified 37 basalt flows that range from 10 to 300 feet thick, and six interflow conglomerates that range from 10 to 100 feet thick, although a more careful examination might reveal more flows. The interflow conglomerates contain abundant round boulders of Keweenaw-type granophyric granite and porphyritic basalt from an unknown source. This sequence, the type locality for the Chengwatana volcanic group, dips about 65 degrees east, and starts within a few hundred feet of the Douglas Fault. Other outcrops of the redefined Chengwatana group that are adjacent to the Douglas Fault dip 40 to 70 degrees east, and those near the Pine Fault dip 10 degrees west. This change in dip is consistent with aeromagnetic patterns that indicate the presence of a southward-plunging syncline that merges

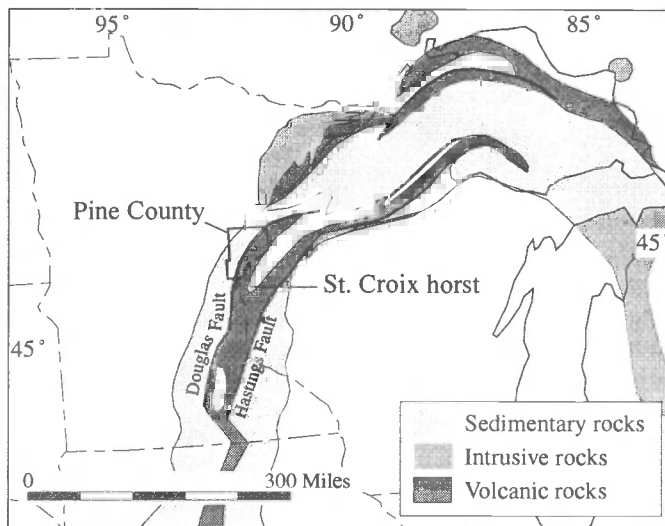


Figure 1. Location of Pine County relative to the St. Croix horst and the Mid-continent rift system.

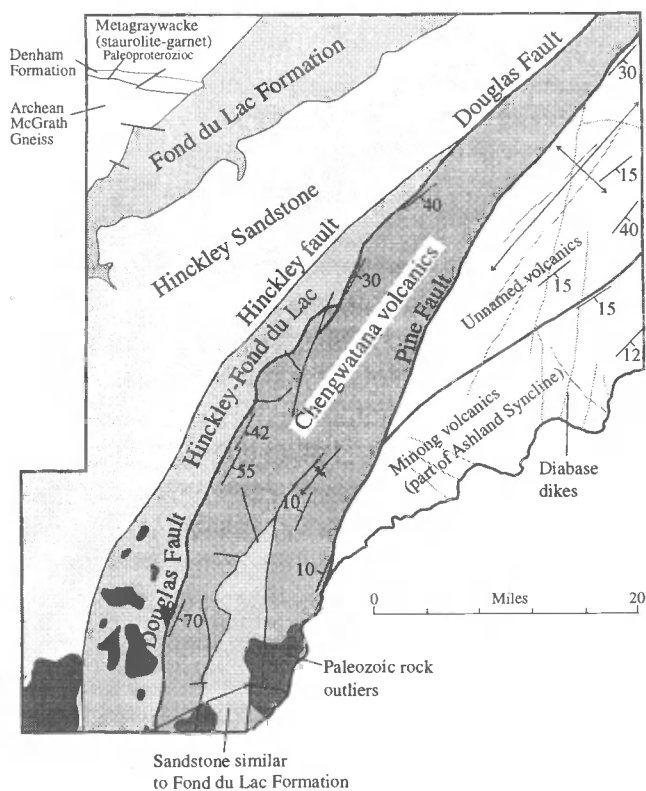


Figure 2. Simplified geologic map of Pine County, Minnesota.

underlying Fond du Lac Formation.

Although the major distribution of rock types has not changed significantly as a result of this mapping effort, we have been able to refine the volcanic stratigraphy of the St. Croix horst. Pronounced linear trends on aeromagnetic maps, essentially parallel to the strike of bedding in volcanic rocks, outline the different volcanic basins, and the measured orientations of volcanic flows in outcrops match those aeromagnetic trends.

This work was done as part of the Pine County Geologic Atlas (Minnesota Geological Survey, County Atlas Series, in prep.), which includes data base, bedrock geology, surficial geology, Quaternary stratigraphy, depth to bedrock and bedrock topography, and mineral resource plates.

References:

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into an unnamed fault (Fig. 2). Hall (1901) recognized this syncline on the basis of the change in dip direction. Sedimentary rocks similar to the Fond du Lac Formation are present on top of the horst at the south edge of the county. The Minong volcanics (approximately 1094 Ma; Nicholson and others, 2001), part of the northeast-plunging Ashland Syncline, lie to the east of the Chengwatana group, and are interpreted to be younger. The Minong volcanics are distinguished from an unnamed central pile of volcanic rocks to the north by divergent linear aeromagnetic patterns. Aeromagnetic lineaments imply that the rocks in this central panel are folded into a doubly-plunging anticline (Fig. 2). Several aeromagnetically-inferred, reverse-polarized diabase dikes cut all three of the volcanic packages in Pine County.

The Hinckley fault (Fig. 2) is proposed as a splay from the Douglas Fault that has displaced the contact between the Hinckley Sandstone and Fond du Lac Formation slightly upward, based on outcrop and geophysical data. North of this fault, the Hinckley Sandstone is typical cliff-forming, uniform and fine-grained quartz arenite, whereas south of the fault the sandstone forms subdued outcrops, is slightly more feldspathic, and contains scattered cobbles of quartzite and minor agate. Locally, tributary streams have cut through this feldspathic sandstone and exposed conglomeratic sandstone, typified by trough cross-beds with trough bases lined by small basalt cobbles, which is assigned to the

STRATIGRAPHY OF THE PALEOPROTEROZOIC DENHAM FORMATION—A CONTINENTAL MARGIN ASSEMBLAGE OF BASALT, ARKOSE, AND DOLOMITE

BOERBOOM, Terrence J., and JIRSA, Mark A.

(Minnesota Geological Survey, boerb001@umn.edu and jirsa001@umn.edu)

The Paleoproterozoic Denham Formation, as originally defined, consists of metamorphosed quartz-rich sedimentary rocks, dolomite, and mafic volcanic rocks (Morey, 1978). The type locality of the Denham Formation, in northwestern Pine County, Minnesota (see figure 2 in Boerboom, this volume), consists of a series of outcrops in and near an abandoned glacial outwash channel. The Denham Formation forms a pronounced linear, positive aeromagnetic anomaly that can be traced from the exposures for 40 miles to the west, to Mille Lacs Lake (Boerboom and others, 1999). This anomaly follows the northern margin of the Archean McGrath Gneiss (2550 ± 14 Ma, Van Schmus and others, this volume). The anomaly is produced by scattered chert-magnetite clasts within fragmental volcanic rocks. The Denham area was mapped as part of the Pine County Geologic Atlas (see Boerboom, this volume). In addition to the outcrops, 15 exploratory drill cores and cuttings holes were utilized in the map interpretation, as was information from water wells contained in the Minnesota Geological Survey County Well Index. The results will be published on the forthcoming 1:100,000 scale geologic map of Pine County, which will include a 1:12,000 scale inset map of the type locality.

The rocks of the Denham Formation have undergone regional, amphibolite-grade metamorphism and at least two periods of deformation. The mafic volcanic rocks are amphibolitic, but contain well-preserved primary features. The granular sedimentary rocks are recrystallized, but retain much of their primary grain size, shape, and composition. In contrast, layers interpreted as pelitic sedimentary rocks are recrystallized to garnet-staurolite-sericite schist. Dolomite is completely recrystallized to marble, with local relict bedding features. The first of two deformation events was synchronous with metamorphism to the garnet zone of the amphibolite facies (Holm, 1986). It produced S1 foliation that typically is parallel to bedding, and a locally strong, shallowly plunging, stretching lineation. The second deformation folded S1 and bedding along steeply dipping axes, and was concurrent with or followed by peak metamorphism that produced staurolite. In the Denham valley, the stratigraphic sequence dips variably to the north, having local F2 folds with overturned limbs. North of the valley, bedding and S1 in graywacke are nearly horizontal, and are deformed into open F2 folds with local crenulation features. North of these graywacke outcrops, the bedding dips to the south, defining a broad, regional-scale, F2 syncline.

Despite deformation and metamorphism, the stratigraphy of the Denham Formation forms a coherent package that is shown schematically on Figures 1 and 2. In this discussion, metamorphic rock names, and the prefix “meta” are omitted for clarity. The base of the Denham consists of interbedded siltstone and cross-stratified pebble conglomerate. This is overlain by coarse-grained and locally conglomeratic arkose that apparently pinches out laterally. The arkose is interbedded with amygdaloidal basalt flows that grade stratigraphically upward (northward) from massive, to pillowed, to fragmental. The volcanic rocks are thickest at the eastern limit of outcrop, where at least four flows of nearly 1000 feet total thickness were recognized, and thin westward to two flows of 300 feet total thickness. This distribution implies that the eastern exposures are nearest to the vent, which may lie beneath the Fond du Lac Formation (Fig. 2). The overlying arkosic and pelitic strata apparently pinch out to the east where the volcanic package thickens, and are not present in drill holes to the north and east of the Denham valley. The northern-most outcrops in the valley consist of very pure dolomite, now marble, having ptlygmatically folded and strongly lineated quartz veins. Drill cores show that the dolomite is at least 500 feet thick, and is overlain by graywacke that is exposed discontinuously to the north for some distance. The contact between dolomite and overlying graywacke is marked by a thin layer of graphitic argillite.

Field and petrographic observations imply that clastic detritus in the Denham Formation was derived in large part from a weathering residuum on the subjacent McGrath Gneiss. Near the contact with the Denham Formation, the McGrath grades abruptly from granite gneiss containing quartz, orthoclase, plagioclase, and biotite; to strongly foliated, quartz- and sericite-rich schist that contains orthoclase, but no plagioclase. The arkosic parts of the Denham Formation similarly lack plagioclase,

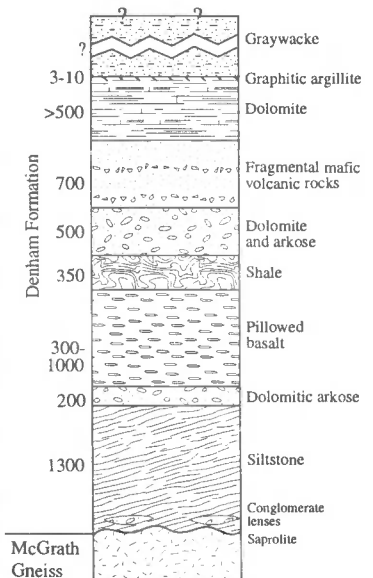


Figure 1. Stratigraphic column of Denham Formation; thicknesses in feet.

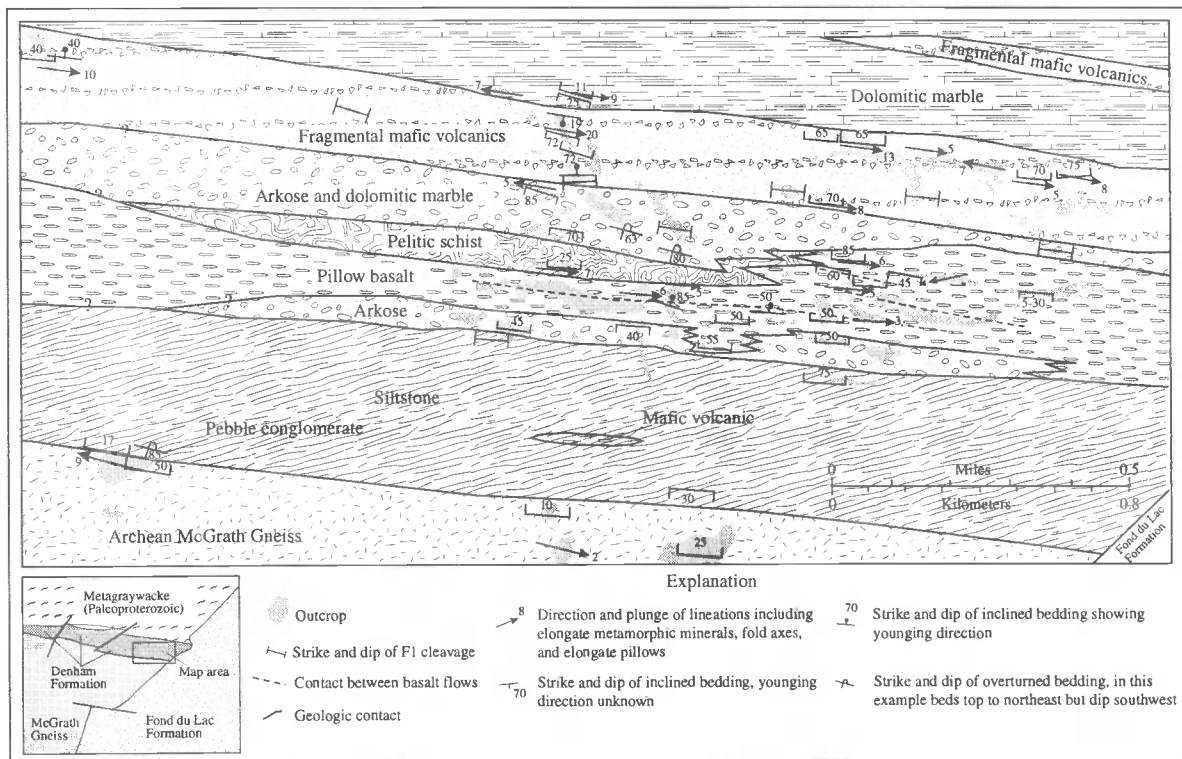


Figure 2. Simplified geologic map of the Denham Formation and adjacent McGrath Gneiss.

and are composed of quartz and orthoclase grains, together with scattered clasts of granitic gneiss. Studies of saprolite developed beneath Cretaceous sedimentary rocks on Precambrian crystalline rocks in southwestern Minnesota may provide an analog (Setterholm and others, 1989). These studies demonstrate that plagioclase is one of the first minerals to alter to kaolinitic clay during the weathering process, and that orthoclase and quartz are the most resistant to weathering. The basal Cretaceous strata locally consists of reworked saprolite, including beds of cross-stratified sandstone and nearly pure kaolinitic shale. Exposures of basal Cretaceous sedimentary rocks locally contain detrital orthoclase and quartz derived by slight reworking of grus-textured, weathered granite. We infer that the same process occurred in the Paleoproterozoic by erosion and reworking of weathered McGrath Gneiss into beds of arkose and kaolinitic shale. These were subsequently metamorphosed to produce recrystallized arkose and staurolite-garnet-sericite schist. Weathering of orthoclase may have liberated potassium for the inferred conversion of kaolinite to sericite during metamorphism.

The Denham Formation is interpreted to represent a rift-margin assemblage deposited during the Paleoproterozoic, genetically similar to, and perhaps temporally equivalent with, the Chocoy Group in Michigan. In this setting, the McGrath Gneiss was part of the continental margin that was weathered and eroded to provide detritus to an evolving rift basin undergoing active, shallow water volcanism. Interbedded arkose and dolomite higher in the stratigraphic section represent foundering of the shelf and deepening water, possibly by subsidence of localized grabens. The lack of arkose in the upper, dolomite-dominated part of the sequence indicates that deposition of coarse detritus was restricted to the shallow, nearshore environment adjacent to the McGrath. The sedimentological gradation of dolomite to graywacke stratigraphically upward indicates further deepening water and associated turbidite deposition. The deformation of the Denham Formation is inferred to be the product of basin closure during the Penokean orogeny.

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GIS Applications for Resource Inventory and Land-use Planning in Wisconsin

B. A. Brown and M. L. Czechanski

Wisconsin Geological and Natural History Survey
Madison, Wi

Wisconsin has recently enacted comprehensive “smart growth” land-use planning legislation that specifically requires counties and local units of government to consider metallic and nonmetallic mineral resources as they develop and adopt a comprehensive plan by 2010. Wisconsin’s nonmetallic mine reclamation rules take effect in 2001. These rules contain provisions to protect undeveloped aggregate deposits from zoning changes, and designate end uses for reclaimed sites, both of which link reclamation into the planning process. Implementation of mandatory reclamation and planning for future supplies both require an inventory of active production sites. In addition, planning requires analysis of geologic data to identify location, extent, and quality of undeveloped resources. Wisconsin Geological and Natural History Survey (WGNHS) is working in cooperation with the U.S. Geological Survey and several state agencies to compile a spatial database of active operations and historic mineral production sites. This database will ultimately link existing state and federal databases containing a variety of information on location, lithology, formation, engineering testing, permit status etc., through a common identification number. WGNHS is also working with county and local governments to inventory active sites and to assemble and assess the quality of geologic data available for comprehensive planning.

Computerized geographic information system (GIS) technology provides powerful new tools for inventory and analysis of mineral resource information. Digital coverages showing the locations of mines, pits, and quarries, and spatial databases documenting the character and extent of deposits can now be easily incorporated with bedrock and surficial geology, soils maps, water resource maps and an ever increasing variety of other environmental, cultural, and political coverages to feed directly into the land-use planning process.

We will present an interactive demonstration of statewide and county geologic and mineral resource coverages recently produced by WGNHS and discuss some of the land-use planning methodologies and applications currently under development.

Field Trip 3: Economic Geology of the Baraboo and Waterloo Quartzites

Bruce A. Brown (1), Frank R. Luther (2), Susan M. Courter (3), James W. Schmitt (4), and Jennifer Lien (5)

Field trip 3 will examine the aggregate and industrial mineral resources of the Proterozoic Baraboo and Waterloo Quartzites of southern Wisconsin. In the Waterloo area twenty miles east of Madison, we will visit a large quarry that produces construction aggregate, breakwater stone, and railroad ballast. We will travel from Waterloo to the Baraboo area, where we will visit five operations that produce a variety of aggregate products.

The Proterozoic quartzites of southern Wisconsin have long been recognized for their unique hardness and durability, refractory properties, and resistance to weathering. Quarries have operated in both areas for more than a century, producing a variety of industrial mineral products and aggregates. Today the major uses for this hard and durable rock are railroad ballast, riprap and breakwater stone, and crushed stone base material. A variety of specialty aggregates ranging from seal coat chips to leachate collection and filter bed material are produced as well.

Stop 1 will be the Michels Materials Waterloo quarry. This operation was opened in 1988 as a source of large stones with high resistance to freeze-thaw loss, for use in constructing breakwaters and erosion control structures on the Great Lakes. Bedding in the Waterloo Quartzite is up to 2 meters thick and joints are widely spaced, allowing blocks up to 10 tons or larger to be quarried. Crushed material was first produced only as a means of disposing of undersize waste rock. Michels continues to produce breakwater stone that exceeds all Corps of Engineers specifications, but much of the current output is crushed for ballast and construction aggregate. We will not have time to visit the historical quarries located to the south of the Michels Quarry which were operated in the early 1900s for refractory blocks, but the geology of the Michels quarry and the old quarry area is described in previous guidebooks by Luther (1992, 1997). From Stop 1 we will travel northwest across the glaciated landscape of Dane and Columbia counties to the Baraboo Range. This drive will provide a look at a classic drumlin landscape.

Stop 2 will be the Williams quarry, operated by the Kraemer Company. This quarry is located on the north limb of the Baraboo syncline and utilizes the Parfrey's Glen Formation, a time-transgressive, near-shore deposit that accumulated around the Baraboo bluffs during Cambro-Ordovician submergence. This quarry produces aggregate that is essentially a quartzite gravel. As the quarry goes deeper into the hillside, more solid quartzite is being quarried. The sedimentary structures in the coarse basal conglomerates and overlying sandstones are spectacular. Stop 3 will briefly examine the 1760 Ma. Rhyolite that underlies the quartzite,

exposed in a road cut on STH 33. Stop 4 will be Milestone Materials Jesse Pit a combination gravel pit/quartzite quarry on top of the south range. Lunch will be in Devils Lake State Park, near the site of a former refractory and abrasive quarry. After lunch we will visit Milestone's Fox Ridge pit and asphalt plant where a variety of quartzite aggregate products are produced, sold, and made into asphalt paving materials. We will next visit the Martin-Marietta Rock Springs Quarry, a historic operation now a major producer of ballast. We will finish at the Kraemer Co, LaRue Quarry on the south range near the site of the historic Sauk and Illinois iron mines. LaRue Quarry contains many examples of sedimentary and tectonic structures as well as examples of quartzite weathering. The trip will return to the Sheraton by 6:00 PM.

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- 1) Wisconsin Geological Survey, Madison, WI
- 2)UW-Whitewater, Whitewater, Wi
- 3) Michels Materials, Inc., Brownsville, WI
- 4) D.L.Gasser Construction, Baraboo, WI
- 5) The Kraemer Company, Plain, WI

RECENT DEVELOPMENTS IN THE MINERALOGY OF THE NINE MILE PLUTON, WAUSAU COMPLEX

BUCHHOLZ, Thomas W., 1140 12th Street North, Wisconsin Rapids, Wisconsin 54494; FALSTER, Alexander. U., and SIMMONS, Wm. B., Department of Geology and Geophysics, University of New Orleans, New Orleans, Louisiana 70148

The mid-Proterozoic Wausau Complex is composed of four intrusive centers; from north to south the Stettin, Wausau, Rib Mountain and Nine Mile plutons (Meyers et al, 1984). The Stettin intrusion is the oldest and most alkalic, and the three other plutons are progressively younger and more silicic. The youngest and most silicic intrusion, the Nine Mile Pluton, is an epizonal anorogenic and heterogeneous granitic intrusion, with locally abundant pegmatites, aplites and miarolitic zones. Miarolitic cavities in the pegmatites as well as miaroles within some phases of the granite attest to shallow levels of emplacement of the pluton. At the surface the granite is altered to a friable disaggregated material called "grus" that is extensively quarried for use as road gravel.

The Nine Mile pluton's pegmatites and aplites contain a wealth of mineral species (Falster, 1981, 1987, Hanson et al., 1998, Buchholz et al., 1999, 2000), which show heterogeneous distribution for many species across the pluton.

Titanium oxide species, such as anatase, brookite, and rutile are abundant in pegmatites of the northern part of the pluton and are far less conspicuous in the central and southern portions. Anatase is by far the most abundant polymorph in the Nine Mile pluton. Niobium and tantalum mineralization is sparse in the northern part of the pluton but becomes more abundant in the central and southern parts. As in most other anorogenic pegmatites, Nb > Ta in Nb-Ta oxides such as ferrocolumbite, uranopyrochlore, liandratite/petschekite, and ilmenorutile. However, in some small-scale, restricted environments late-stage Ta-enrichment is manifest as tapiolite, manganotantalite, strueverite and microlite. In Ta-rich areas there is also a dramatic increase in the abundance of fluorite (Buchholz et al., 1999, 2000). In these areas fluorite becomes a significant mineral phase in some of the pegmatites and even in the adjacent granite.

Beryllium mineralization is dominated by phenakite and bertrandite. Rare beryl, bavenite, and euclase tend to be more common in the northern segment of the pluton. Lithium mineralization is absent but elevated contents of Li are found in micas (lithian biotite and zinnwaldite) in the central and northern parts of the pluton, typically associated with more fractionated mineral species of the Nb-Ta oxides.

LREE-mineralization in the Wausau complex is dominated by phosphates of the monazite group, rhabdophane, and by carbonates of the bastnaesite group. HREE-minerals are essentially restricted to xenotime-group minerals. Both LREE and HREE minerals are found throughout the pluton. Unlike the REE-minerals in the South Platte district in Colorado (Simmons et al., 1987), REE-minerals in the Nine Mile pluton occur as small crystals and grains throughout the pegmatites (Hanson et al., 1998), whereas in the South Platte pegmatites, they form large masses in the core margin and in the replacement units.

Zirconium mineralization is restricted to zircon, which occurs as an accessory mineral throughout the complex, but more Hf-enriched examples are restricted to the high-F environments. Tin is exceedingly rare but it has been found as cassiterite in the central and western portions of the pluton. Some Nb-Ta-oxide minerals from this area contain elevated Sn-content, as well. Manganese mineralization tends to increase from north to south throughout the pluton.

The mineralogy of the Nine Mile pluton exhibits some unusual geochemical trends which are not commonly seen in other anorogenic intrusive systems (which are typical NYF-type environments, i.e. Nb, Y, and F-enriched): The strong Ta-, Hf- and minor Li-, and Sn-enrichment, if only in localized environments, are far more characteristic of LCT-type pegmatites (Li, Cs, and Ta-enriched).

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CAMBRO-ORDOVICIAN STRATIGRAPHY OF SOUTHERN WISCONSIN: SEQUENCE STRATIGRAPHY RULES

Byers, C.W., Dept. of Geology and Geophysics, University of Wisconsin, Madison, WI 53706
cwbyers@geology.wisc.edu

During the past decade, the series of sandstone and carbonate formations that range from Late Cambrian through Late Ordovician have been reinterpreted in terms of the tenets of sequence stratigraphy. Older interpretations relied heavily on the facies concept; while some facies changes are still accepted, others have been superseded by the recognition of subtle unconformities, both at formation contacts and within formations. The new approach breaks the stratigraphic column into numerous unconformity-bounded units, indicating many short-term sea level fluctuations. These cycles are shorter by more than an order of magnitude than the major cratonic sequences originally defined by Sloss.

Rarely do they local sequences show the full range of features expected in a complete cycle: subaerial weathering, lowstand sediments, marine transgressive surface, zone of maximum flooding, offlapping deposits. More typically, the sequences are asymmetric and truncated, with their thicknesses dominated by only one phase of the transgressive-regressive cycle. For example, the Cambrian Jordan Sandstone consists of two shaling-upward marine packages (offlaps) separated by a surface of transgression; lowstand and transgressive deposits are lacking. In contrast, the Ordovician St. Peter Sandstone is composed mostly of eolian lowstand and transgressive marine strata, with a thin cap of Glenwood Shale representing the zone of maximum flooding. Offlapping strata are thin or absent.

Because southern Wisconsin lies on the flank of a cratonic dome, minor unconformities might be expected to grade into conformable sections down dip into the surrounding basins but reappear on other cratonic highs, if the cycles are eustatic in origin.

A preliminary interpretation of new aeromagnetic and gravity data in Wisconsin

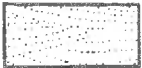
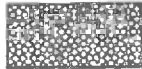
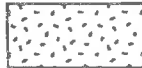
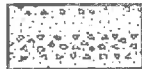
W. F. Cannon, David L. Daniels, Stephen L. Snyder, Suzanne W. Nicholson, USGS, Reston, VA

This geologic sketch map showing Precambrian basement terranes of Wisconsin is an early interpretation of newly acquired and compiled gravity and aeromagnetic data. Geophysical data are supplemented by bedrock mapping in the north and by limited drill hole information and erosional windows through Paleozoic cover in the south. The map presents a new picture of parts of the Precambrian basement in the southern and western parts of the state where it is largely concealed by a thin cover of Paleozoic strata. The map allows inferences on the mineral resources of shallowly buried basement rocks.



Most of the basement of Wisconsin is composed of rocks formed or modified during the Penokean orogeny, roughly 1850 m.y. ago. Isotopic evidence indicates that Penokean crust extends throughout the southern part of the state where younger granite, rhyolite,

and quartzite lie unconformably on it. All were folded and metamorphosed in the foreland of the Mazatzal orogen sometime after 1760 Ma. Archean crust can be confidently traced as far south as the Trempealeau fault, but there is no geologic or isotopic evidence for it south of that structure. The southern Penokean Province appears to be entirely juvenile crust formed during the Penokean orogeny and composes the continental basement for the slightly younger Mazatzal orogeny. Large anorogenic granite plutons were intruded at about 1450 Ma and mafic plutons of unknown age also are widespread. Finally, dikes of diabase, probably related to the Midcontinent rift, cut all other Precambrian units.

-  Diabase dikes
-  Midcontinent Rift- sandstone in flanking basins.
-  Midcontinent Rift- basalt flows and conglomerate in central horst (1100 Ma).
-  Anorogenic granite plutons and related rhyolite. Roughly 1450 m.y. old.
-  Mafic plutons of unknown age. Identified by circular to ovoid corresponding magnetic and gravity anomalies.
-  Quartzite, lesser argillite and schist, minor iron-formation. Unconformable on 1760 Ma rhyolite and granite. Strongly folded and variably metamorphosed.
-  Granite plutons (1760 Ma). Post -orogenic plutons with respect to Penokean orogeny.
-  Rhyolite and epizonal granite (1760 Ma). Contains undifferentiated areas of younger quartzite. Strongly folded in Mazatzal orogeny.

ROCKS OF PENOKEAN OROGEN

-  Fold and thrust belt- Early Proterozoic metasedimentary and metavolcanic rocks and Archean basement gneisses.
-  Pembine-Wausau terrane- Early Proterozoic metavolcanic rocks, syntectonic granite. Archean basement lacking or discontinuous.
-  Marshfield terrane- Archean gneiss and infolded Early Proterozoic metavolcanic and granitic rocks. Mostly granitic gneisses based on low gravity values.
-  Marshfield terrane- Archean gneiss and infolded Early Proterozoic metavolcanic and granitic rocks. Mostly mafic gneiss based on high gravity values.
-  Southern Penokean terrane- poorly known unit with high gravity and magnetic anomalies. Probably mostly mafic metavolcanic rocks. Contains undifferentiated areas of quartzite and 1760 Ma rhyolite and granite.
-  Southern Penokean terrane- poorly known unit with low gravity and magnetic anomalies. Probably mostly felsic rocks. Contains undifferentiated areas of quartzite and 1760 Ma rhyolite and granite.
-  Northern limit of Paleozoic strata.

REGIONAL ARSENIC ANOMALIES SHOWN BY NURE STREAM SEDIMENT AND HYDROGEOCHEMICAL DATA IN NORTHERN WISCONSIN AND MICHIGAN

W. F. Cannon, USGS, Reston, VA

L. G. Woodruff, USGS, Mounds View, MN

A regional arsenic anomaly in northeastern Wisconsin and the upper peninsula of Michigan is identified in the NURE (National Uranium Resource Evaluation) surveys of stream sediments and ground water. The anomalous region is about 250 miles long in north-south direction and as much as 75 miles wide. Examination of the anomaly with regard to bedrock and glacial geologic features suggests that it is a composite anomaly caused by two different bedrock sources of arsenic and variations in glacial dispersal of arsenic-rich bedrock. The two sources differ in their expression. One, the Michigamme anomaly is expressed mostly in stream sediments and to a lesser degree in well water. The other, the Fox River Valley anomaly is expressed strongly in well water, but has almost no stream sediment signature.

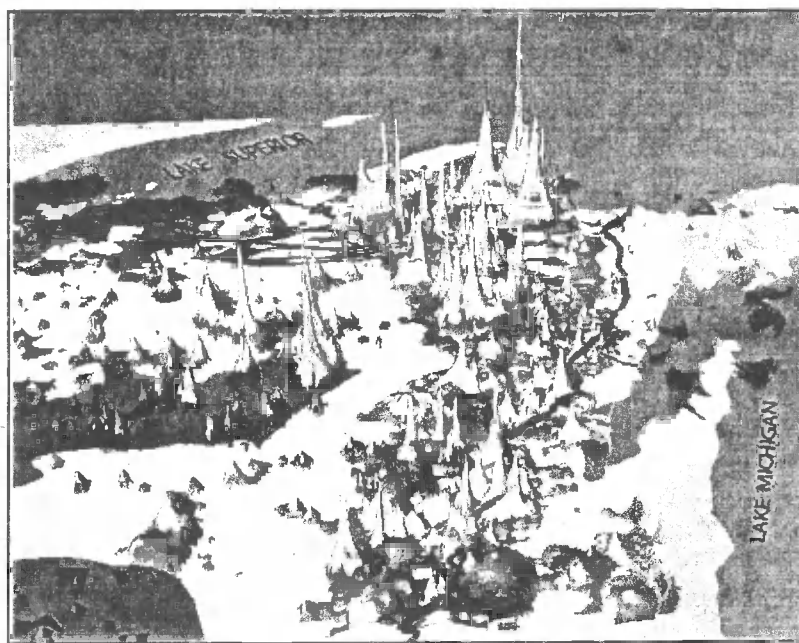


Figure 1. Composite arsenic anomaly map of northern Wisconsin and Michigan. Base is map of glacial lobes. The shaded semi-transparent surface shows a combined anomaly from both NURE stream sediment and well water data. The surface shows the more anomalous of the two data sets relative to the regional mean values of 2 ppm As for stream sediments and 0.65 ppb As for well water. Only areas with arsenic above regional mean values are shown in the 3-D surface. The surface is defined by about 3200 stream sediment analyses and 3500 well water analyses. Black unit is arsenic-bearing Michigamme Formation and heavy line is the outcrop trace of arsenic-bearing Ordovician sandstone.

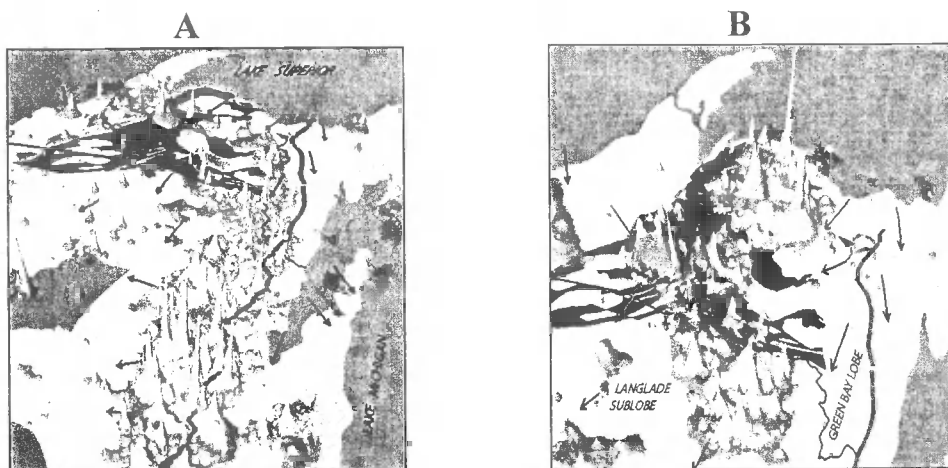


Figure 2. A. The Fox River Valley anomaly shown by well water. Anomaly lies mostly west of arsenic-rich sandstone. B. The Michigamme anomaly shown by stream sediments. Anomaly location is controlled by location of Michigamme Formation and glacial features. Base map as in Figure 1. Arrows show direction of ice movement.

The Fox River Valley Anomaly

The Fox River Valley arsenic anomaly is best shown by NURE well water data and is only weakly expressed in stream sediment data (see Figure 2A). Arsenic values range up to a maximum of 60 ppb in well water. Interestingly, a great majority of the wells that show high arsenic in the NURE data lie west of the outcrop trace of the gently east-dipping arsenic-bearing sandstone and also west of the area where more recent data has identified an arsenic problem in wells. Bedrock in the western area of the anomaly is mostly Cambrian sandstone and Precambrian crystalline rocks, mostly granite. No arsenic source is known in these rock units. The anomaly is mostly within the area once occupied by the Green Bay glacial lobe and lies in a down-ice direction from the Ordovician sandstone. Glacial transport of arsenic-rich bedrock into the anomalous area appears to be a significant factor, suggesting that the immediate source of arsenic in well water west of the outcrop of the arsenic-rich sandstone is the unconsolidated glacial deposits.

The Michigamme Anomaly

The Michigamme anomaly is most strongly expressed in stream sediment data, but also occurs in well water data (Figure 2). It is geographically restricted by a combination of bedrock and glacial geology. The northern extent of the anomaly in stream sediments coincides very closely with the northern extent of the outcrop belt of black slate within the Precambrian Michigamme Formation. The eastern extent of the anomaly in northern Michigan is defined by the western margin of the Green Bay glacial lobe, which did not cross arsenic-rich bedrock. To the south, there appears to be glacial dispersal of arsenic-rich bedrock in both the Green Bay lobe and Langlade sublobe in northern Wisconsin where high arsenic values in stream sediments and well water extend more than 50 km south of the outcrop belt of the Michigamme black slates.

PALEOMAGNETIC STUDY OF PALEOPROTEROZOIC ROCKS IN THE ANIMIKIE GROUP, NORTHERN MINNESOTA

CHANDLER, Val W. and MOREY, G.B.

(Minnesota Geological Survey, chand004@umn.edu and morey001@umn.edu)

A pilot study was conducted to investigate paleomagnetism in the Pokegama Quartzite and Biwabik Iron Formation of the Paleoproterozoic Animikie Group. The quartzite was sampled at six sites along the northern margin of the central and western parts of the Mesabi Iron Range, with three to six oriented samples collected per site. The iron-formation was sampled at four sites at a small outlier located to the north of the range near Pike Mountain; one to five oriented samples were collected per site. All samples are fresh and unoxidized. Core and cube specimens were cut from the field samples, and selected specimens were subjected to stepwise alternating-field and thermal demagnetization. Observed directions of magnetization have considerable scatter, and some specimens, especially those of magnetite-rich iron-formation, were highly unstable during stepwise demagnetization. Nonetheless, several samples of each unit yielded stable, well-clustered magnetizations which appear to be associated with the early history of the rocks. With regard to thermal demagnetization, high blocking temperatures (greater than 600°C) are consistent with hematite as the primary carrier of stable magnetizations in the iron-formation. Hematite is an original or very early diagenetic phase in the iron-formation, whereas magnetite is a diagenetic phase that may have formed much later in the paragenetic scheme. Unstable or nulled magnetizations above thermal levels of 550°C in Pokegama specimens imply that magnetic minerals other than hematite may be present.

Correcting for a bedding dip average of 10° to the south, the stable magnetizations of the Biwabik and Pokegama formations are directed at declinations/inclinations averaging 242°/65° and 289°/85°, respectively. The Pokegama ($\alpha=13.3^\circ$) and Biwabik ($\alpha=21.9^\circ$) directions cannot be discriminated from each other, or from a direction derived previously for the stratigraphically equivalent Gunflint Iron Formation in Canada (Symons, 1966) within 95 percent confidence. Our Animikie directions also overlap with those of a secondary imprint recognized to the north in the pre-Animikie Kenora-Kabetogama dikes by Halls (1986), who attributed it to a regional episode of hydrous alteration that tended to be more pronounced southwards, towards the Animikie basin. A working model that is consistent with present observations proposes that the diagenesis and subsequent magnetization of the Animikie rocks were accompanied by a regional groundwater flow system that may have been concentrated near the base of the Animikie sequence.

The results of this study indicate that further paleomagnetic work on the Animikie Group rocks will be valuable, although the selection of sites that will produce useful results may pose some problems. Remaining tasks include determining if the Pokegama and Biwabik directions are truly indiscriminate from each other as well as from other Paleoproterozoic directions reported in the area. Ultimately, tightly constrained paleopole(s) can be combined with high-resolution radiometric dating to significantly improve the Paleoproterozoic apparent polar wander path for North America.

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AN OVERVIEW OF AEROMAGNETIC MAPPING IN MINNESOTA

CHANDLER, Val W., Minnesota Geological Survey, 2642 University Avenue,
St. Paul, MN 55114, chand004@tc.umn.edu

AN OVERVIEW OF AEROMAGNETIC MAPPING IN WISCONSIN

MUDREY, M.G. Jr., Wisconsin Geological and Natural History Survey,
3817 Mineral Point Rd., Madison, WI 53705, mgmudrey@facstaff.wisc.edu

MINNESOTA

Magnetic methods have long been used by geologists in Minnesota to help investigate poorly exposed Precambrian bedrock. In fact, the Cuyuna iron range, which was discovered in 1904 by dip needle, was the first mining district in the United States that was discovered wholly by a geophysical method. The first large-scale magnetic project in Minnesota occurred after WWII, when George M. Schwartz, then-director of the Minnesota Geological Survey (MGS), made a cooperative arrangement with the U.S. Geological Survey (USGS) for surveying in Minnesota using the newly developed aeromagnetic method. Although the priority of this early work was locating new iron ore resources, the usefulness of the new method in mapping Precambrian geology was quickly realized, and by 1950 over 40,000 square miles of northern Minnesota had been covered by this method. During the 1960s while P.K. Sims was director of the MGS, the USGS aeromagnetic coverage over the entire state was completed, and an integrated program of geologic mapping using aeromagnetic and gravity data began. These efforts culminated in 1970 with the publication of a state geologic map, the first since 1932.

By the mid-1970s, the potential of the USGS aeromagnetic data had been realized, and newer, higher resolution data were needed. Through the efforts of Matt Walton, then-director of the MGS, and Robert Hansen, then-executive director of the Legislative Commission on Minnesota Resources (LCMR), a new state-wide program of high-resolution aeromagnetic surveying began in 1979. Funding came primarily from the LCMR, with additional contributions of data from the USGS, the U.S. Steel Corporation and the Geological Survey of Canada. The data obtained earlier was flown at one mile line spacing with 1000 feet terrain clearance, and much of the new flying was conducted at ¼ mile spacing with 500 feet terrain clearance. In addition, the new data were digital and could be readily subjected to a variety of computer-based processing and enhancement schemes to assist in geologic interpretation and mapping. State-wide coverage was completed in 1991, and the new aeromagnetic data, used in conjunction with an improved gravity database, have dramatically improved Precambrian geologic mapping in Minnesota. Virtually all Precambrian bedrock in the state has been re-mapped at a scale of 1:1,000,000 or larger. The new geologic maps, as well as the geophysical data used to help make them, will be useful to a variety of scientific and economic investigations for many years to come.

WISCONSIN

T.C. Chamberlin's geologic staff began mapping in northern Wisconsin in 1870s as a continuation of mapping in southern Wisconsin. It was recognized that conventional geological techniques did not provide sufficient information in the glacially covered,

geologically complex areas of the Gogebic Range. C.E. Wright of the Chamberlin's Wisconsin Geological Survey sent a sketch to instrument maker Gurley in Troy, New York, of a "dipping needle" based on a design he had seen from Sweden. The determination of the inclination and declination of the magnetic field had been well established by R.D. Irving and C.R. Van Hise of the U.S. Geological Survey by the late nineteenth century. Beginning in 1913, W.O. Hotchkiss and colleagues of the Wisconsin Geological and Natural History Survey (WGNHS) mapped large areas of northern Wisconsin by conventional and magnetic methods to assess mineral value for taxation. In 1935, C.K. Leith, R.J. Lund and A. Leith of the U.S. Geological Survey were able to produce a reasonable regional geologic map of the Lake Superior Precambrian that was based on conventional geology, mineral mapping, and extensive magnetic surveys.

Using fluxgate magnetometers developed during World War II, G.P. Wollard and his students undertook regional magnetic surveying in Wisconsin in the early 1960s. Of note is the regional aeromagnetic map of Wisconsin in 1964 by R.W. Patenaude and colleagues, who mapped Wisconsin on a 10-km line spacing at 1000-m elevation.

Prior to 1972, more detailed surveys were limited to small areas in support of geologic programs in southwestern and central Wisconsin. In 1972, the WGNHS received a small grant from industry to initiate surveys in central Wisconsin. With this seed and grants from Upper Great Lakes Regional Commission, the WGNHS and University of Wisconsin-Oshkosh professor John Karl conducted a survey of a large area in northern Wisconsin. That survey was completed in 1977 with a "fill in the holes" grant from U.S. Geological Survey. These and subsequent public surveys were flown on lines spaced at 805 m, and oriented in a north-south direction. The altitude was draped to topography at 305 m above ground level.

Interest in massive sulfide exploration in the 1980s resulted in many private surveys, some of which were released to the public through the WGNHS. More recently (1997-1999) the U.S. Geological Survey completed surveying the remaining land areas of Wisconsin. The release of these data on CD-ROM is stimulating a reevaluation of the regional geologic fabric of the upper Midwest.

Remaining activities include an adjustment of the surveys to a common base and preliminary analysis of the newly acquired data by W.F. Cannon and others.

The statewide coverage, used in conjunction with an improved gravity database, will dramatically improve subsurface geologic mapping. The new geologic maps as well as the geophysical data used to help make them will be useful to a variety of scientific and economic investigations for many years to come.

STRUCTURE, STRATIGRAPHY AND PUNCTUATED EVOLUTION OF MINNESOTA'S MINERAL EXPLORATION ARCHIVES

David Dahl, Minnesota Department of Natural Resources, Hibbing, Mn 55746

A project to catalog the content of Minnesota DNR's mineral exploration archives for remote digital access has provided a substantial "opportunity" to better understand the structure and relationships among some 15,000 unpublished mineral exploration documents, and the 100+ exploration programs they came from. Together, the documents provide a mosaic of evolving mineral exploration methods and exploration models, and reflect changing exploration focus over time.

In the past, archive users have often had a sense of déjà vu when researching Minnesota's archives. Indeed, during the process of cataloguing the content, some 25% of the archive documents were found to be duplicates of existing information. In some cases, more than a dozen copies of a document existed in the files. The lineage of that duplication, and the reasonable geographic motif that led to that duplication offer several lessons about the geographic nature of mineral exploration programs and storage of mineral exploration data for future geologic research.

Within government activities, remote access to the mineral exploration archive provides a needed input for more responsive local and regional planning, and offers a historical background for mineral resource management decisions. In conjunction with online comparison to other data sets such as DOQ's, DRG's, DEM's, Public Land Survey, aeromagnetic data, published geologic maps, land use, landsat, soils and other baseline information, the exploration data archives can now be used to more quickly glean unique insights about previous exploration efforts and to develop insights for new geologic and geophysical exploration and research.

NEW AEROMAGNETIC MAP OF WISCONSIN EXAMINED IN A REGIONAL CONTEXT

DANIELS, David L., dave@usgs.gov, NICHOLSON, Suzanne W., swnich@usgs.gov, CANNON, William F., wcannon@usgs.gov, U.S. Geological Survey, MS 954 National Center, Reston, VA 20192, and KUCKS, Robert P., rkucks@usgs.gov, U.S. Geological Survey, MS964 DFC Box 25046, Denver, CO 80225

The new aeromagnetic map of Wisconsin portrayed in color at a scale of 1:500,000, is the result of digitally blending grids of 22 surveys flown between 1948 and 1999. The composite grid features 1) a resolution of 250m, and 2) a common elevation; all surveys were either flown at, or digitally continued to, an elevation of 1000 ft (305m) above mean terrain, prior to assembling into a state grid. The U.S. Geological Survey acquired all recent data in the state (1988 to 1999) amounting to about 77,000 line-miles. The digital flightline data for three of these surveys have recently been released on CD-ROMs. These data were added to earlier USGS surveys and 4 surveys acquired by Wisconsin Geological and Natural History Survey. Flight lines are ½-mile apart or less for 95% of the state, giving the aeromagnetic map nearly uniform specifications, and making the map an excellent tool for USGS mineral resource investigations.

The Wisconsin grid has also been digitally blended with data from surrounding areas (Chandler, 1991; Hildenbrand and Kucks 1984, 1991) to form a preliminary regional aeromagnetic map of the North-Central US that reflects the structure of Precambrian basement rocks (see gray-scale index map). The regional map will be shown in color at a scale of 1:2,000,000.

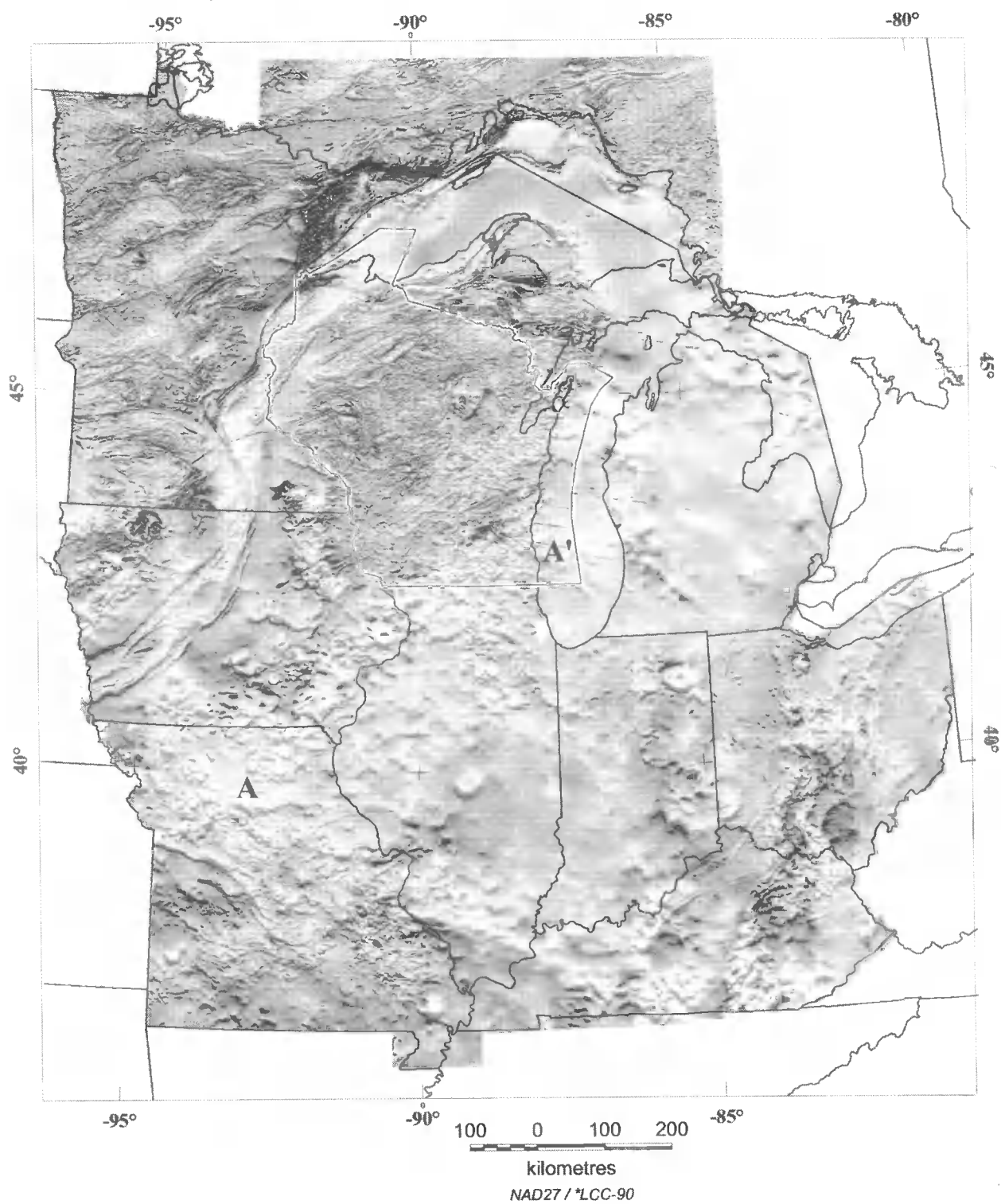
The aeromagnetic data of the region include some surveys of widely spaced flight lines (3 to 6 miles), particularly in northwestern and central Illinois, Lake Michigan, and the lower-peninsula of Michigan. These are areas where higher resolution data would be helpful to better define basement geology.

Aeromagnetic features observed within Wisconsin can be traced into surrounding states. These features include: 1) high-amplitude linear anomalies that record the upturned edges of Keweenaw basaltic lava flows of the Midcontinent Rift System, and the smooth magnetic field of the flanking sedimentary basins; 2) abundant, narrow, linear magnetic anomalies probably generated by diabase dikes show a variety of trends across the region. (These anomalies are prominent only in areas of high-resolution surveys); 3) a strong ENE directed aeromagnetic fabric in areas of exposed Precambrian rocks in northern Wisconsin, Minnesota, Michigan's northern Peninsula, and Canada that records highly-deformed basement rocks, and 4) an aeromagnetic fabric with no preferred trend and abundant circular to arcuate anomalies, that characterizes much of the area to the south. This undirected fabric may reflect large areas of anorogenic igneous rocks, although part of the undirected fabric could also be due to greater depth to basement and lower survey resolutions. In SE Wisconsin a belt of high overall magnetic intensity lies within this area of undirected fabric, and is characterized by a series of high-amplitude, oval to circular anomalies. The belt continues SW through Illinois and Iowa into Missouri and eastward across Lake Michigan (A-A' on figure). The circular to oval anomalies suggest plutonic complexes in the basement.

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Aeromagnetic Anomaly Map of Wisconsin and North-Central US



MIDDLE PROTEROZOIC TECTONIC HISTORY OF THE CENTRAL TUSAS MOUNTAINS, NORTHERN NEW MEXICO, AND COMPARISON WITH THE BARABOO INTERVAL, SOUTHERN LAKE SUPERIOR REGION

DAVIS, Peter B 1, WILLIAMS, Michael L. 1, BOWRING, Samuel A 2, and RAMEZANI, Jahan 2.
(1) Department of Geosciences, Univ of Massachusetts, Amherst, MA 01003, davis@geo.umass.edu, (2) Earth, Atmospheric & Planetary Sciences, Massachusetts Institute of Technology

The similarity between mid-Proterozoic quartzite units of the Baraboo interval, and the Ortega quartzite of northern New Mexico, has been recognized for decades. (Dott 1993) These similarities are based on sedimentary characteristics and the general timing of deposition, deformation and metamorphism of these supermature quartzite units. Plate tectonic reconstruction models also show a trend in the bedrock's mantle separation age extending from southwest to northeast that connect these units. (Hoffman 1988)(Figure#1).

However, drawing a meaningful correlation between them across a 1000-mile separation is extremely difficult because of the sparse nature of intervening exposure, and the uncertainty in the absolute timing of events. Recent work in the Tusas Mountains of northern New Mexico has further constrained the tectonic history that affected the Ortega quartzite among other units, and therefore might shed light on this tentative correlation.

Recent field mapping, geochronology, and petrologic analysis in the Tusas Mountains has focused on a northwest-southeast striking enigmatic discontinuity that is suspected to be a late mesoproterozoic ductile fault. This fault juxtaposes higher-grade complexly deformed supracrustal immature to mature metasediments (which includes the Ortega Quartzite) and felsic metavolcanics found to the south against lower grade immature metasediments and mafic to felsic metavolcanics and intrusives found to the north (Figure#2). Ductile deformational features present in these rocks can be grouped into three generations. A strong bedding parallel S1 foliation is ubiquitous, however there are few F1 folds. D2 features include reclined tight to isoclinal folds with a strong SW dipping S2 foliation, and SW plunging stretching lineations (L2), sub-parallel to fold axes. Kinematic indicators suggest transport on this lineation was to the northeast. These structures are more pronounced south of the discontinuity. D3 produced east-west trending open folds, and either a newer crenulation cleavage, or reactivated S2. In some localities D3 has reoriented F2 folds into F3 folds. Metamorphic conditions can also be grouped into three generations. M1 conditions reached lower greenschist facies. M2 reached greenschist facies conditions. M3 is discontinuous across the NW-SE discontinuity from upper greenschist to the north, to sub-amphibolite to the south (550°C -4.5kb). Timing of all three of these deformational events were traditionally correlated with the 1.67-1.65Ga. Mazatzal orogeny. New geochronologic data of 1.67-1.69 Ga. for the weakly deformed Tusas granite suggests that the strong fabric in the Moppin group host rock was produced before 1.69Ga., possibly during the Yavapai Orogeny. A refined age for the Tres Piedras Granite, and a syn-D1 dike, is now 1.67-1.69 Ga. is interpreted to suggest that the first two fabrics in the granite, directly correlative to regional fabrics, are indeed the result of 1.68-1.65Ga. Mazatzal tectonism. These data also further constrain the age of deposition of the Hondo group, which includes the

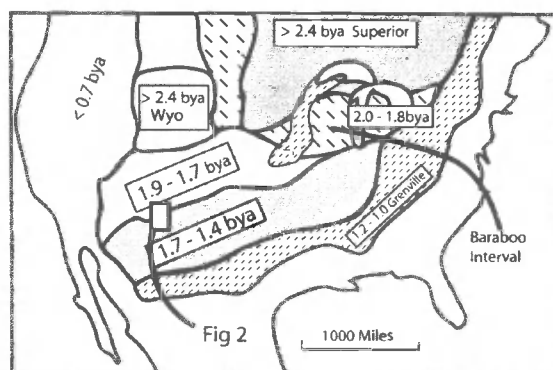


Figure #1 Age Domains of Central North America

Ortega Quartzite, to older than 1.69 -Ga., but younger than the underlying 1.70-1.71Ga. Burned Mountain rhyolite. D3, which increases in strength from north to south across the Tusas Mountains, was recently constrained in the southern Tusas Mountains to 1.45-1.40Ga. (Bishop et al 1996).

The earliest tectonic event represents an early phase of thrusting with syn-orogenic plutonism, and is primarily preserved to the northern portion of the Tusas Mountains. The second event, thought to be the result of additional thrusting with folding, is preserved throughout the Tusas Mountain range. The third event significantly overprinted much of the range both tectonically and thermally. Its effects are thought to be the result of the burial of the range to the mid-crust leaving the region to eventually cool isobarically, erasing much of the evidence for earlier events. The effects of this overprint however strong in the southern half of the tusas, diminish at the discontinuity, and are poorly preserved to the north.

This refined model for the central Tusas Mountains of northern New Mexico provides a better framework with which to compare the Baraboo Interval in future regional models. Both regions contain a generalized supracrustal sequence of rhyolite followed by laminated to massive supermature quartzites. Constraint on the timing of deposition of both quartzite units is between approximately 1.71 – 1.65 Ga. Deformation is constrained between deposition and respective thermal event around 1.45 Ga. (Medaris 1996). Some have suggested that folding of the Baraboo Interval occurred around approximately 1.63 Ga., during which whole-rock Rb-Sr systems were reset over the region. The 1.45 Ga. thermal and tectonic event that affected both the southern Lake Superior Region and the Tusas Mountains is thought to be related to the anorogenic magmatic event (Anderson 1992).

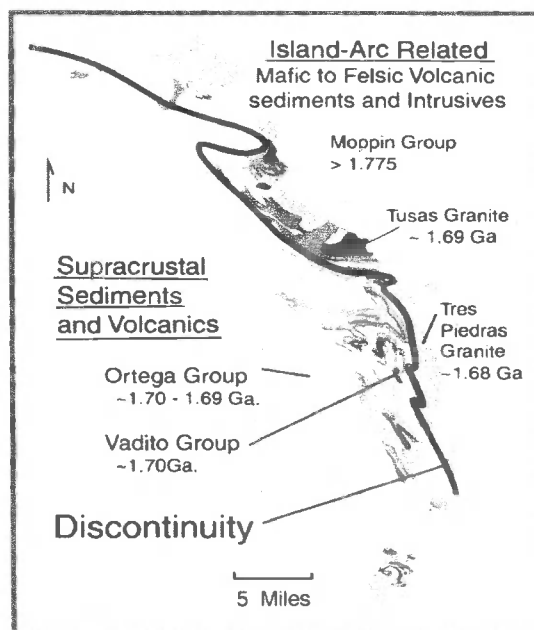
Proterozoic rocks of northern New Mexico and the Baraboo Interval of the southern Lake Superior region are windows into important tectonic processes. These widely separated windows reveal different structural levels and foreland proximities along a general orogenic trend across the Laurentian margin as it grew through mid-Proterozoic time.

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Figure#2 - Tectonic Map of the Tusas Mountains, NM

SOME OBSERVATIONS FROM THE WILLIAMS QUARRY EXPOSURE: EVIDENCE OF DEBRIS FLOW DEPOSITS IN THE PARFEYS GLEN FORMATION?

PHILIP FAUBLE, Wisconsin Department of Natural Resources, P.O. Box 7921, Madison, WI 53707-7921; faublp@dnr.state.wi.us

JENNIFER LIEN, Kraemer Company, P.O. Box 235, Plain, WI 53577; jenl@mhtc.net

A quarry located on the north side of the North Range of the Baraboo Syncline, originally developed to mine sand and gravel from a quartzite conglomerate of the Parfeys Glen Formation, has recently expanded into in-situ Baraboo Quartzite. This provides a unique opportunity to observe the Precambrian/Cambrian unconformity and its relationship to the overlying conglomeratic deposits.

The undifferentiated quartzite conglomerate and conglomeratic sandstones, found in a broad band on both sides of the North and South Ranges of the Baraboo Hills, were first described in detail by Dalziel and Dott (1970). They inferred that these deposits were the result of wave action eroding and transporting quartzite from the ancestral Baraboo Hills during the transgression of the late Cambrian seas. These deposits were later named the Parfeys Glen Formation by Clayton and Attig (1990), who split the formation into three components: a talus conglomerate directly adjacent to the quartzite, a conglomeratic sandstone and a sandstone unit that may or may not contain quartzite pebbles. Although the causes of the lithologic differences between individual units within the Parfeys Glen Formation were unclear, they considered it likely that the talus conglomerate was considerably older than the adjacent sandstone.

At present, the quarry exposure is approximately 15 meters high, 200 meters long, north facing, and generally oriented east to west, parallel to the axis of the North Range. There are three distinct lithologies exposed along the quarry wall consisting of the following, from the base of the exposure to the top: in-situ quartzite, a very coarse quartzite conglomerate, and a finer-grained conglomeritic sandstone that gradually transitions to a quartz sandstone.

In-situ Quartzite: An irregular, rounded outcrop of Precambrian Baraboo Formation quartzite is exposed at the base of the quarry wall. The quartzite is slightly overturned and dips steeply to the north. The main quarry face roughly parallels the strike of the quartzite beds. The largest exposure of quartzite is located just west of the center of the quarry wall and seems to represent a subdued topographic high prior to deposition of the upper units.

The most striking feature of the in-situ quartzite is the presence of a smooth, rounded, gently undulating erosional surface along the unconformity between the quartzite and the overlying conglomerate. This smooth surface is present on both vertical and near horizontal exposures. While smooth, this surface is not varnished and does not possess striations, gouges or percussion marks. There are no obvious potholes developed in this surface, but shallow features that resemble small chutes are common.

Quartzite Conglomerate: Overlying the smooth erosional unconformity developed on the quartzite is a quartzite conglomerate of varying thickness. This deposit is thinnest on the top of the quartzite knob, thickest within two low areas that flank the western and eastern sides of the knob, and gradually thins to the east. An exposure along the western wall of the quarry indicates that the coarse conglomerate gently dips northward.

The conglomerate is composed of large rounded boulders of quartzite suspended in an unsorted, massive matrix of sand, rounded pebbles and cobbles. The conglomerate is poorly cemented and seems to lack any materials smaller than fine sand. All lithic fragments larger than sand are composed of quartzite or quartzite breccia likely derived from the nearby outcrops of Baraboo quartzite. Depending on quarry development, exposed quartzite boulders can range in size from 1 to over 3 meters in diameter along their longest visible axis. The largest boulders appear to be concentrated along the quartzite unconformity and the upper margins of the deposit. As first noted by Dalziel and Dott (1970), boulders larger than 2 meters in diameter tend to be angular or possess smooth rounded features on only one or two faces. Boulders smaller than about 2 meters are almost always completely rounded. There does not appear to be any clear fabric or preferred orientation to the larger clasts within the deposit.

Conglomeratic Sandstone: Above and to the north of the quartzite conglomerate is a conglomeratic sandstone that thickens dramatically from less than 3 meters directly above the quartzite knob to over 10 meters at the northern edge of the quarry. It is composed of horizontally bedded strata consisting of alternating layers of sand and pebble conglomerate. This deposit is likely marine in origin, with abundant glauconite, sometimes occurring in thin, discrete beds, and abundant *Scolithus* burrows in the sand layers. The sandstone is visibly finer grained and much better cemented than the quartzite conglomerate directly below it. In contrast to the large boulders found in the conglomerate, an informal, random sampling of 50 of

the largest pebbles visible in the sandstone exposed along the eastern wall of the quarry indicated a long axis diameter no greater than 20 cm.

On the eastern wall of the quarry, the horizontally bedded conglomeratic sandstone can be seen to neatly onlap the north-dipping conglomerate. Above the conglomerate/sandstone unconformity, sandstone drapes the larger boulders projecting above the surface of the conglomerate deposit. Along the southern wall of the quarry, the conglomeratic sandstone extends from above the quartzite conglomerate to within about 3 meters of the top of the exposure where it abruptly transitions into a well cemented quartz arenite. This transition does not appear to be an unconformable surface, but likely reflects the drowning of the pebble source as the transgressing Cambrian seas covered the crest of the North Range.

Conclusions: The exposure at the Williams Quarry clearly preserves and records three distinct events that occurred on the North Range of the ancestral Baraboo Hills sometime from the late Precambrian to the late Cambrian. First, topographically prominent exposures of the Baraboo quartzite were eroded into a series of smoothly rounded features. Second, conditions changed and a deposit of unsorted quartzite debris (conglomerate) covered the erosional surface, filling in swales and blanketing hillslopes. Lastly, a marine deposit of sand and locally derived pebbles covered the conglomerate.

The exact processes and conditions that produced the smooth weathering/erosional surface on the in-situ quartzite are unknown. However, the nature of the unsorted quartzite conglomerate indicates that it is likely the result of subaerial mass movements of material eroded from the crest of the North Range. We suggest that these movements took place in the form of large debris flows that generally followed drainages developed in the ancestral Baraboo Hills. Similar coarse conglomeritic deposits adjacent to Precambrian erosional surfaces have been noted in other regions. The lowest facies of the Upper Cambrian Lamotte Sandstone in southeast Missouri contain locally-derived rhyolite boulder conglomerates that have been interpreted as small alluvial fans formed, in part, by debris flows adjacent to the incised Precambrian bedrock of the ancestral St. Francois Mountains (Houseknecht, 1978).

The wide grain size distribution of the conglomerate, ranging from fine sands to boulders several meters in diameter, the larger clasts suspended within in an unsorted mass, and the lack of clear grading or internal structures, closely matches the description of debris flow deposits in Coussot (1996). Debris flow deposits result from the rapid transport and mass emplacement of a highly viscous slurry of water and debris. Evidence that the quartzite debris within the conglomerate was transported and not merely weathered in place can be seen at the unconformable boundary between the in-situ quartzite and the conglomerate, just east of the bedrock knob. The in-situ quartzite at this location contains an extensive quartzite breccia, very similar to the Rock Springs (Abelman's Gorge) breccia (Dalziel and Dott, 1970). Directly above the smooth, truncated surface of the eroded breccia lie large boulders and cobbles that contain no evidence of breccia. Conversely, large grains of breccia-bearing material can be seen in the conglomerate mass above other areas that lack in-situ breccia.

Many other questions concerning this conglomerate deposit remain unanswered. The source area and the processes that produced the rounded boulders, cobbles and sand that make up the conglomerate remain enigmatic. Thick deposits of Paleozoic and glacial sediments obscure the most likely quartzite source areas near the crest of the North Range, south of the quarry. If the top of the conglomeratic sandstone represents the drowning of the uppermost quartzite outcrop, then the source area for the conglomerate may be no more than a few meters higher in elevation than the top of the quartzite knob exposed in the quarry wall. This doesn't preclude the formation of a debris flow because, once a flow is initiated, it may continue to move over slopes as low as a few degrees. Debris flows are also very poor rounding agents, so it is likely that the quartzite clasts in the deposit were already rounded smooth prior to transport. Features visible in a few of the conglomerate boulders suggest that at least some of the rounding occurred in situ, possibly in response to intense chemical weathering.

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Contrasts in the Geologic and Hydrochemical Occurrences of Arsenic Contamination of Groundwater in Eastern Wisconsin

Gotkowitz, M.B., Wisconsin Geological and Natural History Survey, 3817 Mineral Point Road, Madison, WI 53705 mbgotkow@facstaff.wisc.edu

Schreiber, M.E., Department of Geological Sciences, Virginia Tech, Derring Hall, Blacksburg, VA 24061 mschreib@vt.edu

Simo, J.A., Department of Geology and Geophysics, University of Wisconsin-Madison, 1215 W. Dayton St, Madison, WI 53706 simo@geology.wisc.edu

Clusters of arsenic-impacted wells are found in two areas of eastern Wisconsin: the Fox River valley (east-central Wisconsin) and the Lake Geneva (southeastern Wisconsin) areas. In the Fox River valley area, arsenic concentrations up to 12,000 ppb have been measured in groundwater from a Cambrian-Ordovician sandstone aquifer. An arsenic-rich, sulfide-bearing, secondary cement horizon (SCH) is commonly present at the top of the Ordovician St. Peter Formation. Within the SCH, arsenic occurs in pyrite and marcasite and in iron oxyhydroxides, but not as a separate arsenopyrite phase. Whole rock concentrations of arsenic within the SCH range from about 15 to 675 ppm. Core samples show that arsenic-bearing minerals are also present in the St. Peter below the SCH.

Several pieces of evidence support the hypothesis that oxidation of sulfides is the cause of high (>100 ppb) concentrations of arsenic in well water, including 1) the presence of arsenic-bearing sulfides in the aquifer, 2) water-chemistry data that show a positive correlation between arsenic, iron, and sulfate and negative correlation between arsenic and pH; and 3) nearly identical sulfur isotopic signatures in pyrite and dissolved sulfate. There is a strong correlation between high arsenic concentrations and the occurrence of intersecting elevations of the SCH and water levels within wells. This relationship provides the basis for our conclusion that atmospheric oxygen, introduced to the SCH through well boreholes, provides an oxidant to the system.

However, the cause of more commonly encountered, moderate (less than 100 ppb) arsenic concentrations found in wells in the Fox River valley is not well understood. The variability of the thickness of the SCH and the associated mass of arsenic within the sulfides, as well as the local availability of an oxidant to fuel the oxidation of the SCH, may contribute to the spatial variability in arsenic concentrations in well water. The available water quality data are not sufficient to determine if other geochemical mechanisms, such as desorption or reductive dissolution of arsenic-bearing iron oxyhydroxides, control the moderate arsenic concentrations measured in well water.

Our preliminary work in the Lake Geneva area indicates that geologic and hydrogeologic conditions leading to a cluster of arsenic-impacted wells in this part of the state are not similar to those in the Fox River valley. Arsenic has been detected in wells open to the Quaternary deposits, Silurian dolomite, and the Cambrian-Ordovician sandstone. Arsenic concentrations in rock samples from these aquifers range from 1.4 to 18 ppm; aqueous concentrations in well water range up to 80 ppb. Water chemistry in arsenic-contaminated wells is not consistent with sulfide oxidation, and sulfide mineralization has not been observed in rock samples collected from the area. These results indicate that other geochemical mechanisms of arsenic release, such as the reduction of arsenic-bearing iron-oxides, may also affect Wisconsin groundwater supplies.

THREE NEW ZIRCON DATES FOR THE MIDCONTINENT RIFT, NORTH SHORE, MINNESOTA: MORE DATA, MORE QUESTIONS

GREEN, J. C., Geological Sciences, U. of MN Duluth, Duluth, MN 55812; DAVIS, D. W., Royal Ontario Museum, 100 Queen's Park, Toronto, ON M5S 2C6; and SCHMITZ, M. D., Earth and Planetary Sciences, MIT, 77 Mass. Ave., Cambridge, MA 02139

U/Pb zircon dates have been obtained for three significant localities on the North Shore, with some intriguing results.

Skeletal zircons from the residual monzodiorite at the top of the Duluth Complex Layered Series in Duluth give an age of 1098.5 ± 1.3 Ma (DWD). This agrees with the 1099.3 ± 0.3 Ma age determined by Paces and Miller (1993) from a segregation within the upper part of the Layered Series. The skeletal crystal habit assures that the new date represents the magma crystallization age, not inherited crystals.

A rhyolite flow exposed below the quarry in the southeast flank of Carlton Peak near Tofte gives an age of 1092.6 ± 2.0 Ma (DWD). This is the youngest date yet found on the North Shore. This local volcanic sequence is apparently isolated by faults from the rest of the North Shore Volcanic Group, including its uppermost sequence, the Schroeder-Lutsen basalts (SLB), and it is clearly younger than the 1096.6 ± 1.9 Ma Palisade rhyolite (Davis and Green, 1997) which unconformably underlies the SLB. Since it has been suggested (Miller et al., 1995) that the SLB is an outlier or fringe of the Portage Lake Volcanics (dated at 1096-1094 Ma, Davis and Paces, 1990), this new date implies either that the SLB is actually considerably younger than the PLV, or that the Carlton Quarry sequence is an isolated remnant of heretofore unrecognized late volcanic activity on the Minnesota flank of the MRS. Furthermore, the dated quarry sequence is intruded by the anorthosite-xenolith-bearing Carlton Peak diabase, making that still younger and not coeval with dated units of the Beaver Bay Complex (~ 1096 Ma, Paces and Miller, 1993).

Finally, a granite xenolith in the Terrace Point basalt flow southwest of Grand Marais (Green, 2000) is dated at 1096.7 ± 1.4 Ma (MDS). Since this medium-grained, upper mesozone-looking biotite granite must have crystallized slowly at many kilometers' depth before being broken off and carried to the surface in the basalt magma, this implies that the Terrace Point flow (basal flow of the SLB) is significantly younger than the granite. A coarse-grained segregation vein within the Schroeder basalts was collected and processed, but no zircons or baddeleyite were found, leaving the SLB still undated.

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INITIAL RESULTS OF IN SITU ELECTRON MICROPROBE (EMP) AGE DATING OF MONAZITE FROM THE SOUTHERN LAKE SUPERIOR REGION: CONFIRMATION OF WIDESPREAD GEON 17 METAMORPHISM

HOLM, D., dholm@kent.edu, Dept. of Geology, Kent State University, 44242; JERCINOVIC, M.J., and WILLIAMS, M., both at Dept. of Geosciences, University of Massachusetts, Amherst, MA 01002.

Introduction. Like most orogens, the pattern and degree of Proterozoic metamorphism preserved across the 1870-1830 Ma Penokean orogenic belt is highly variable. Widespread 1630 Ma metamorphism of much of the Penokean arc terrane in Wisconsin is well documented (see Table 4 of Peterman et al., 1985, CMP; Romano et al., 2000, PreC. Res.) and intrusion of the 1470 Ma Wolf River batholith certainly produced thermal overprinting in central and southern Wisconsin (Holm et al., 1998, GSAA; Naymark et al., 2001, GSAA). Until recently, intermediate pressure and higher temperature metamorphism both north and west of the arc terrane (northernmost Wisconsin, northern Michigan and east-central Minnesota) has been attributed to the geon 18 Penokean orogeny (see overview by Geiger and Guidotti, 1989, Geoscience Wisc.). Three separate studies published in the late 1990's however (Schneider et al., 1996, CJES; Marshak et al., 1997, Geology; Holm et al., 1998, AJS) proposed the presence of a widespread geon 17 amphibolite facies overprinting metamorphism. In order to better establish the timing of intermediate grade metamorphism in the southern Lake Superior region we have started a microprobe monazite geochronology study of selected metamorphic samples from east-central Minnesota and northern Wisconsin. EMP dating of monazite is currently emerging as a rapid and accurate means of geochronology, and is most easily applied to the Precambrian where the Pb concentration often allows greater analytical precision (Williams et al., 1999, Geology).

Results from East-Central Minnesota. We dated monazite from a staurolite-garnet schist outcrop (sample MN-29) of the metamorphosed Little Falls Formation collected on the Mississippi River (Blanchard Dam). Thermobarometric, thermochronologic, and textural analysis of this and other metamorphosed samples led Holm et al. (1998) to suggest two episodes of amphibolite facies metamorphism (a geon 18 Penokean M1 and a younger geon 17 M2 associated with emplacement of abundant post-tectonic plutons). Eight EMP spot analyses on three separate monazite grains yielded U-Th-P ages ranging from 1755 Ma down to 1667 Ma (mean age of 1719 ± 21 Ma). The oldest ages are concordant with abundant Ar/Ar mica and hornblende ages obtained throughout the region (Holm and Lux, 1996, Geology; Holm et al., 1998).

Results from northern Wisconsin. We have obtained preliminary data from two drill core samples of garnet-biotite-sillimanite schist located near Park Falls, Wisconsin. These samples occur within the recently identified fault-bounded, sillimanite-bearing panel just north of the Niagara Fault zone (Park Falls subterrane of Cannon et al., 1998, ILSG). Sample PF-2-311 yielded a mean age of 1710 ± 43 Ma from 3 spots analyzed on 3 separate monazite grains. Sample BL-2-252 (located nearby the first sample) revealed a distinctly chemically zoned grain which produced distinct core and rim ages of 1805 Ma and 1695 Ma, respectively.

Finally, we sampled the well known kyanite bearing outcrop located near the town of Powell. This sample is located within the higher pressure fault-bounded panel identified as the Powell subterrane (Cannon et al., 1998). Ten EMP spot analyses on three separate grains yielded U-Th-Pb ages ranging from 1780 Ma to 1747 Ma (mean age of 1765 ± 7 Ma).

Implications and Conclusions. These data, although preliminary, appear to support other independent evidence for a widespread, post-Penokean, geon 17 intermediate grade metamorphic event in the southern Lake Superior region. In Minnesota, geon 17 metamorphism appears concentrated within the internal zone of the orogen where abundant post-tectonic plutons exist. To the north in the medial zone earlier geon 18 metamorphic ages are preserved in garnet grade rocks (Schneider et al., 2001, ILSG). In northern Wisconsin the age of metamorphism in structural panels preserving contrasting metamorphic conditions (sillimanite versus kyanite) appears to be dominantly geon 17 although a hint of earlier Penokean metamorphism is apparently preserved (see also Schneider et al., 2001, for Penokean metamorphic ages preserved north of the Niagara Fault zone in northern Michigan). These metamorphic age constraints suggest that the fault-bounded subterrane may have been juxtaposed *after* the Penokean orogeny during a period of widespread metamorphism followed by rapid unroofing (as suggested by geon 17 cooling ages).

We conclude that microprobe monazite geochronology holds promise for unraveling the timing of multiple metamorphic and tectonic events in the Lake Superior region as it has for other portions of the southern margin of Laurentia (Williams et al., 2001, ILSG).

AGE OF THE HUMBOLDT GRANITE, NORTHERN MICHIGAN: IMPLICATIONS FOR THE ORIGIN OF THE REPUBLIC METAMORPHIC NODE.

HOLM, D., dholm@kent.edu, Dept. of Geology, Kent State University, 44242; VAN SCHMUS, W.R. and MacNEILL, L.C., both at Dept. of Geology, Univ. of Kansas, Lawrence, KS, 55045.

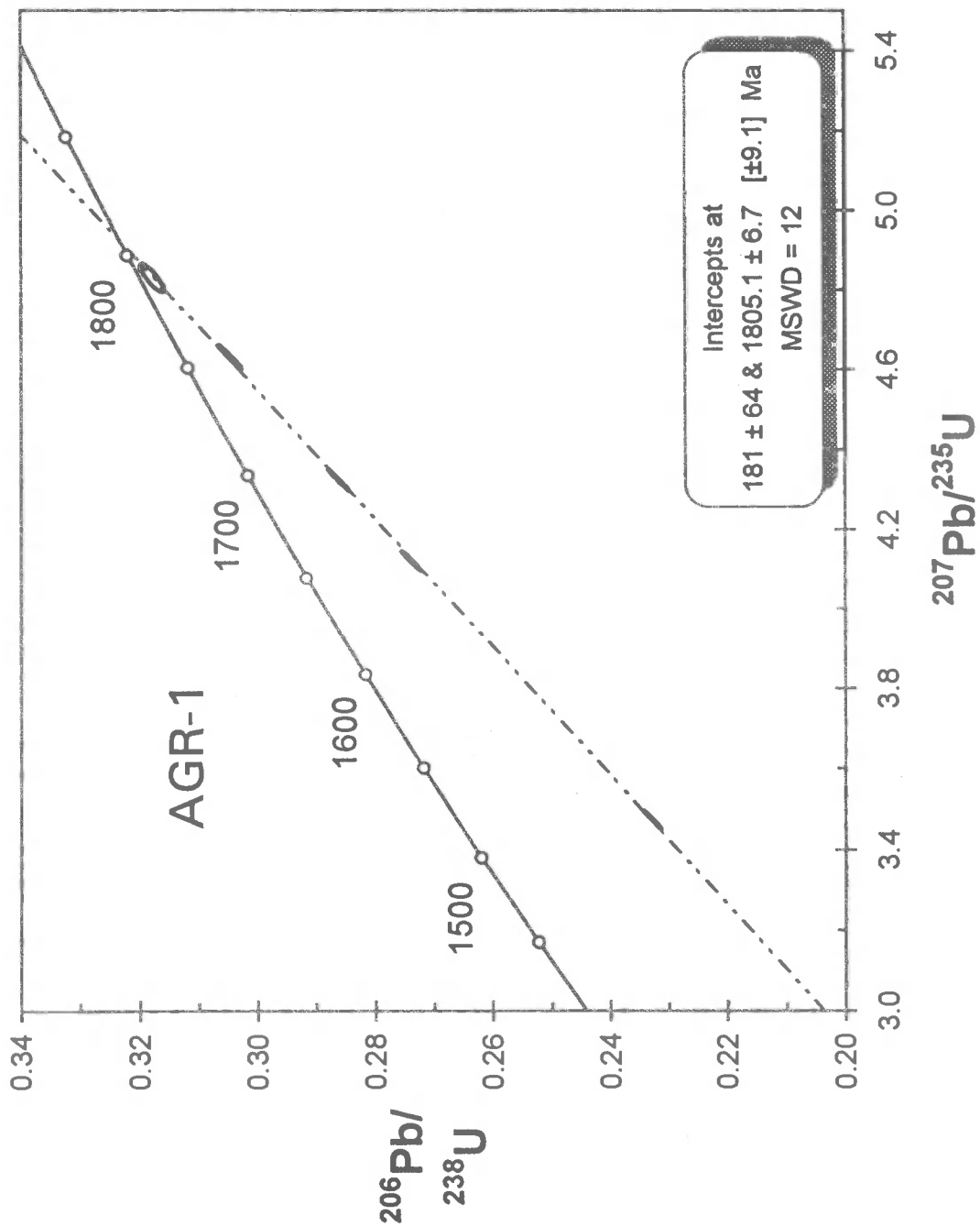
The alkali-feldspar granite near Humboldt lies on the northeastern edge of a large negative gravity anomaly that is roughly coincident with the Republic metamorphic node. Hornblende, muscovite, and biotite Ar/Ar ages obtained from country rock across the node are 1720-1670 Ma (Schneider et al., 1996). A whole-rock Rb/Sr minimum age of 1733 ± 25 Ma on the granite was reported by Schulz et al. (1988). The concordance of the whole-rock age with the thermochronologic data led Schneider et al. (1996) to infer that post-tectonic plutonism caused the metamorphic nodal pattern. In order to test this hypothesis we obtained both U-Pb and Ar/Ar mineral age data on the Humboldt granite.

U-Pb zircon results. Six single-grain analyses of somewhat turbid grains separated from a sample of the Humboldt granite (AGR-1, collected by Holm) yielded a linear array on a conventional U-Pb concordia diagram. All six analyses yield an upper intercept age of 1806 ± 21 Ma, although one analysis is clearly off the line. Elimination of this analysis yields an age of 1805 ± 7 Ma with a lower intercept of 181 ± 64 Ma. One analysis is nearly concordant and has a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1802 ± 6 Ma. Thus it is clear that the crystallization age is significantly older than the Ar retention age or the Rb/Sr age, which is a common situation in the Lake Superior region.

Ar/Ar mica results. We dated three separate mica fractions obtained from a coarse phase of the granite. In order to test for possible intracrystalline age gradients we furnace step-heated the rim and core portion of a coarse muscovite grain. Both analyses yielded essentially concordant plateau dates of 1712 ± 6 Ma (core) and 1703 ± 6 Ma (rim). Step-heating of biotite did not produce a reliable plateau age. Incremental ages increased monotonically with the three highest temperature fractions giving ages between 1670 and 1700 Ma (amounting to 45% of the gas released). These Ar/Ar results are comparable to mica Ar/Ar ages from older bedrock of the Republic region and are concordant within error with the whole-rock Rb/Sr age of the Humboldt granite.

The crystallization age of the granite indicates that it could not have provided the heat source needed to form the Republic metamorphic node at ca. 1720 Ma. We cannot rule out the possibility of a younger geon 17 intrusive body existing in the Republic subsurface, although thus far geon 17 plutons have been documented predominantly south of the Niagara fault zone (the sole exception being the 1781 Ma Park Falls granite, Van Schmus et al., 2001). A combination of anomalously high basement heat production rates (Attoh, 2000) together with basement remobilization (i.e., Marshak et al., 1997) might better explain geon 17 low P/high T metamorphism in the Republic region of northern Michigan.

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NEW VOLUME CALCULATIONS FOR THE PYROCLASTIC ERUPTIONS ASSOCIATED WITH THE STURGEON LAKE CALDERA COMPLEX, NORTHWESTERN ONTARIO: IMPLICATIONS FOR THE SCALE OF ARCHEAN VOLCANIC PROCESSES

GEORGE J. HUDAK

Department of Geology, University of Wisconsin Oshkosh, Oshkosh, WI 54901

DEAN M. PETERSON and RONALD L. MORTON

Department of Geology, University of Minnesota – Duluth, Duluth, MN 55812

The Archean Sturgeon Lake Caldera Complex (SLCC) of northwestern Ontario comprises a north-facing, homoclinal, bimodal sequence of caldera-associated, greenschist facies metamorphosed, volcanic, intrusive and sedimentary strata with a composite thickness of nearly 4500 meters and a strike length of at least 25 km (Morton et al., 1991). At least three volcanic-associated massive sulfide (VMS) orebodies were formed as sub-seafloor replacement deposits within quartz-phyric, pumice-rich vitric tuff within the caldera complex (F-Group, Mattabi, and Sturgeon Lake); the other three orebodies in the region (Sub-Creek Zone, Creek Zone, and Lyon Lake) were probably formed from structural deformation of the Sturgeon Lake Mine (Hudak, 1996).

Hudak et al. (2000) have divided the caldera complex into three stratigraphic sequences. The Pre-Caldera Sequence (PCS) is composed of a 200-2100 meter thick succession comprising subaerial basalt lavas, scoria-rich volcanoclastic rocks, and very minor rhyolite lavas that formed prior to the development of the caldera complex. The Early Caldera Sequence (ECS) comprises a 650-1300 meter thick succession of subaerial rhyolite ash tuff formed immediately prior to the formation of the caldera edifice, and subaqueous coarse heterolithic breccias, syneruptive aphyric and quartz-phyric pumice-rich vitric tuffs, and andesitic to rhyolitic lava flows formed prior to, or simultaneously with, the Mattabi VMS orebody. The Late Caldera Sequence (LCS) is composed of a complex, 500-1500 meter thick succession of subaqueous quartz- and quartz-plagioclase-phyric vitric tuffs, andesitic to dacitic lava flows, lava domes, and cryptodomes, resedimented syn-eruptive ash-rich mudstones, ash-rich sandstones, and lithic lapillistones, as well as post-eruptive tuffaceous mudstones, tuffaceous sandstones, tuffaceous breccias, and Algoma-type iron formations. Hudak (1996) and Morton et al. (1998) have shown that the stratigraphic relationships indicate that the SLCC developed in a manner similar to the well-known caldera cycle of Smith and Bailey (1968).

The presence of exceptionally well-preserved, often delicate primary lithological textures within the volcanoclastic and volcanic rocks in the south Sturgeon Lake region has allowed individual rock units and their facies equivalent deposits to be distinguished and correlated. These features indicate that only minor amounts of structural deformation, and probably only minor amounts of diagenetic compaction, have occurred within the intracaldera volcanoclastic rocks that are present. This, along with the steeply dipping nature of the strata in the region, allows us to make very accurate areal calculations of the volcanoclastic strata by means of geographic information system (GIS) analysis. Although arguably speculative, volumes of individual pyroclastic eruptions have been calculated using the average thicknesses of each of the major pyroclastic units within the caldera, the strike lengths of the pyroclastic units, and the assumption that these units were deposited within a circular caldera.

The results of our eruption volume calculations are contained in Table 1. These calculations indicate that, although Archean in age, the SLCC eruptions were similar in scale to eruptions associated with Cenozoic arc-associated caldera systems. Thus, it appears that not only was the caldera cycle (Smith and Bailey, 1968) established by Late Archean time, but that pyroclastic eruptions occurring in Archean arc-associated caldera complexes were similar in scale to pyroclastic eruptions occurring in more recent arc-associated caldera systems. Although more detailed studies on the evolutionary processes and eruptive volumes need to be completed at other well-preserved Archean caldera complexes, these results may provide us with clues to Late Archean tectonic and petrological processes.

Table 1. Volume Estimates of Sturgeon Lake Caldera Complex Eruptions

<i>Eruption</i>	<i>Caldera Sequence</i>	<i>Estimated Volume (km³)</i>
Jackpot Lake	Pre-Caldera	8.8
High Level Lake	Early Caldera	16.6
Bell River	Early Caldera	1.9
Mattabi	Early Caldera	28.7
Lower "L"	Late Caldera	3.0
Middle "L"	Late Caldera	6.9
Upper "L"	Late Caldera	3.5

Table 2. Volume Estimates of Historic Caldera Eruptions

<i>Eruption</i>	<i>Estimated Volume (km³)</i>	<i>Source</i>
Pinatubo (1991)	4-5	Lipman, 2000
Krakatau (1883)	10	Lipman, 2000
Santorini (3.6 ka)	25-30	Lipman, 2000; Cas and Wright, 1987
Tambora (1815)	25	Cas and Wright, 1987
Vandever Mtn Tuff (T-J)	13-26	Kokelaar and Busby, 1992
Taupo (1.8 Ka)	30-35	Lipman, 2000; Cas and Wright, 1987
Kuwai (~1450)	32-39	Monzier et al., 1994

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A PRACTICAL EXERCISE IN METALLIC MINE RECLAMATION - LADYSMITH, WISCONSIN

T.C. HUNT, Director of the Reclamation Program, School of Agriculture,
University of Wisconsin - Platteville, Platteville, WI 53818

In November 1968, Great Lakes Exploration, a subsidiary of Kennecott, intersected copper mineralization along the Flambeau River south of Ladysmith, Rusk County, Wisconsin. This discovery and the rising environmental consciousness in Wisconsin lead to nearly 25 years of legislation, engineering evaluation, and environmental regulation. The Flambeau Mine was officially opened on July 31, 1993 and by the time the mine closed in 1997, 1.9 million short tons of ore averaging 8.9 percent copper and 0.10 ounces per ton of gold were produced. This mine was unique in that all of the ore was shipped directly to smelters for metal recovery; there was no beneficiation on site. Reclamation of the property was an important part of the entire mine design.

Kennecott Minerals' Flambeau Mine reclaimed their open pit copper mine under the jurisdiction of Wisconsin's environmentally sensitive metallic mining laws; viewed by many as the most strict in the nation. It was alleged that Wisconsin's modern mining laws were prohibitive, but the Flambeau Mine provides a case study demonstrating viable mining and reclamation within the constraints of rigorously protective regulatory requirements can happen.

The mine site is adjacent to the Flambeau River, one of Wisconsin's premier whitewater canoeing area, and surface water, groundwater, and mine water were important parts of the mining plan. Reclamation was initiated prior to the completion of mining. Flambeau backfilled the open pit mine by layering mine waste and carbonate rock to control acidity, and reclaimed the surface using state-of-the-science ecological restoration methods. The company brought the surface of the former pit to its approximate original contour, rebuilt pre-existing intermittent stream channels, restored native plant communities, and developed a series of biofilters and wetlands to enhance runoff quality. A trail system opens the site to the public for recreational pursuits such as hiking, cross-country skiing, and bird watching. Bald Eagles and black bears are frequent visitors to the site. Visual inspection and statistical analysis of surface water samples present evidence that the site is stabilizing and that the hydrologic system is functioning as designed. Monitoring continues on the site, and the vegetative sampling results indicate the reclaimed mine site is on the desired trajectory for plant community development, diversity, cover, plant frequency, and productivity.

This experience of a well designed and implemented mine plan, in conjunction with a well designed and implemented reclamation plan, illustrates that mining and the environment can be compatible.

THE EARLY GABBROIC SERIES OF THE MIDCONTINENT RIFT SYSTEM: CONTINUED ASSESSMENT OF MAGMATIC ORIGINS

JERDE, Eric A. (e.jerde@morehead-st.edu) and SALVATO, Daniel J. (student), Department of Physical Sciences, Morehead State University, Morehead, KY 40351; THOLE, Jeff and WIRTH, Karl R., Geology Department, Macalester College, St. Paul, Minnesota, 55105

The Early Gabbroic Series of the Midcontinent Rift System (MCR), informally known as Nathan's Layered Series (after Nathan, 1969), is comprised of numerous tabular and sheetlike intrusions just south of the Gunflint Trail in the vicinity of Poplar Lake in extreme northeastern Minnesota. A U-Pb zircon date of 1106.9 ± 0.6 Ma has been obtained for one of the units in this series (Paces and Miller, 1993), making it among the oldest materials associated with the MCR. Nathan (1969) identified 27 separate units, given the letter designations A-Z and AA in their inferred chronological order. The chronological sequence was based entirely on cross-cutting relations and discordances 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 unique 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-norites), F-G (oxide-rich olivine gabbro), M (gabbro-norite), and P-Q (troctolites to gabbros). These intrusions can fairly be considered to be the principal events in the evolution of the Early Gabbroic Series. A key aspect of this series of rocks, and one that led to the initial interest by H.D. Nathan in the 1960s, is that several units contain large amounts of Fe-Ti oxides. In places oxides comprise in excess of 30% of the rock (Nathan, 1969). However, among the major units listed above, only unit F-G is notable for high abundances of oxide, exceeding 60% at some locations. Until now, no chemical analyses have been available for rocks of this series.

Initial modeling of magma crystallization (Jerde, 2000) indicated that the principal units of the early Gabbroic Series may be the result of polybaric fractionation. In such a scenario, units A-B, and P-Q formed through crystallization at 6 kb, with M being more fractionated. Unit F-G could have formed through extensive crystallization at 1 kb. Oxide phases are favored by fractionation at lower pressures, resulting in the higher amounts seen in unit F-G.

Results of initial chemical analyses of bulk rocks (Table 1) show that both high-Al, low-Ti magmas and low-Al, high-Ti magmas are present. This is an interesting result since it has long been assumed that the earliest magmatic products of the MCR were all low-Al and high-Ti. The oxide-rich nature of the Early Gabbroic Series was consistent with this assumption. From this data, it is evident that unit F is significantly different from other units. Unit F may not be associated with unit G at all, and chemically resembles unit A. This is in marked contrast to the interpretation of Nathan (1969).

The mineral data for some of the units shows variations consistent with multiple magma compositions, particularly among the pyroxenes. Among pyroxenes, Unit C appears to resemble unit P-Q, which was originally thought to be much younger. The variations in pyroxene may be additional evidence for polybaric fractionation since pressure differences plays a pivotal role in the appearance of pyroxene during crystallization. Most plagioclase is of an intermediate An content, showing very little variation among the units.

The latest field efforts have focused on individual units, simply to be systematic. These probably represent individual intrusions, and once each one is examined, they can hopefully be placed into a broader context. The first unit examined was P-Q. This unit is present in a single band extending from Poplar Lake for approximately 15 kilometers to the west. It is interesting to note that Unit P is repeated, appearing twice in the magma stack (Fig. 1). In both instances, unit J is present stratigraphically above unit P. Unit J has a very characteristic appearance, with large ophitic pyroxenes (up to 3 cm) and layers of coarse grained material rich in Fe-Ti oxides. In most instances, when the top of unit P is approached, material very much like unit J appears, suggesting a gradational contact. A definitive contact between P and J was not observed at any location. Chemical and mineral data, along with the completely gradational contact between P (a gabbro) and Q (a troctolite), indicate that these are probably a single intrusion that has undergone continuous fractionation. It is possible that J is simply a late stage fractionate, formed after P. The repetition of unit P may reflect a second pulse of magma, or perhaps faulting (a thrust?) There is some indication that the two layers of unit P may have different compositions (compare sample J0-14 with the other unit P compositions in Table 1). One sample does not make a difference, however, and a definitive answer awaits further analysis, which will take place in the next few weeks.

Recent studies of anorthosite-bearing intrusions such as the Kiglapait, Laramie, and Nain intrusions, has indicated that anorthosites can be produced through fractionation of a high-Al, high-Fe basaltic magma at pressures of 9-14 kb (Scoates and Lindsley, 2000). Such high-Al, high-Fe melts are consistent with low degrees of melting of an Fe-rich, enriched mantle source. Fractionation of these melts at higher pressures (~14 kb) produces strong Fe enrichment and oxide phases appear early in the crystal assemblage. In such a scenario, the fractionation produces a ferrodiorite which is in equilibrium with anorthosite of an intermediate (An_{50-60}) composition. Enrichment of Si during fractionation is only possible at low pressures due to a thermal divide between cpx and opx at pressures in excess of 5 kb (Scoates and Lindsley, 2000). If such a magma were parental to the Early Gabbroic Series, it suggests that some of the Early Gabbroic Series units may be siblings to the liquids that formed the anorthositic series further to the south. Additional crystallization modeling is definitely needed to explore this new potential source for rocks of the early stages of the Midcontinent Rift development.

Table 1. Preliminary whole-rock compositions of major units from the Early Gabbroic Series

Sample	Unit	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	mg#
J9-38	A	48.26	0.25	20.01	1.28	8.50	0.12	8.75	8.92	2.94	0.25	0.04	99.33	61.8
J9-35	A	49.47	0.25	17.93	1.32	8.80	0.14	9.40	9.05	2.75	0.23	0.03	99.39	62.6
J9-32	B	52.63	0.55	13.84	1.54	10.24	0.23	10.70	8.38	2.13	0.22	0.02	100.51	62.1
J9-31	B	52.66	0.75	16.36	1.11	7.42	0.16	8.03	11.08	2.65	0.42	0.13	100.83	63.0
J9-2	C	50.02	0.50	16.23	1.31	8.72	0.15	8.99	11.68	2.46	0.25	0.03	100.37	61.8
J9-46	F	51.53	1.12	15.08	1.26	8.38	0.16	8.24	12.05	2.34	0.33	0.10	100.64	60.7
J9-24	G	45.65	3.73	15.74	1.99	13.27	0.18	4.73	9.60	2.87	0.61	0.57	98.96	35.9
J9-23	G	47.31	4.79	12.98	1.99	13.26	0.21	5.41	9.39	2.68	0.81	0.31	99.14	39.0
J9-22	G	47.06	3.05	15.14	2.19	14.60	0.20	4.88	7.36	3.13	0.93	0.76	99.32	34.4
J9-29	J	51.48	1.61	22.98	0.92	6.14	0.08	1.76	9.58	3.80	0.98	0.07	99.44	31.0
J9-41	M	48.09	1.30	18.93	1.38	9.20	0.13	7.43	9.74	2.85	0.29	0.03	99.40	55.9
J9-40	M	48.29	2.64	22.28	1.26	8.41	0.09	1.76	10.15	3.78	0.48	0.11	99.26	24.7
J9-37	M	47.03	0.41	17.52	1.62	10.79	0.15	10.25	7.71	2.63	0.29	0.07	98.47	59.9
J9-27	P	48.31	1.83	15.56	1.50	9.98	0.16	7.23	12.81	2.40	0.23	0.02	100.07	53.2
J9-17	P	49.20	1.80	15.40	1.45	9.68	0.16	7.15	12.09	2.44	0.37	0.13	99.90	53.7
J0-10	P	49.30	1.72	14.53	1.50	9.97	0.17	7.84	12.60	2.32	0.21	0.06	100.22	55.3
J0-11	P	47.43	2.15	15.81	1.67	11.14	0.16	6.46	11.80	2.45	0.29	0.03	99.39	47.7
J0-14	P	49.63	1.15	16.14	1.30	8.63	0.15	7.25	12.94	2.32	0.19	0.02	99.72	56.9
J9-26	Q	51.70	0.93	14.68	1.21	8.03	0.17	7.64	12.79	2.58	0.47	0.11	100.32	59.9
J0-4	Q	48.17	0.17	18.48	1.72	11.46	0.16	8.16	7.12	3.14	0.35	0.07	99.00	52.8
J0-13	Q	49.03	0.12	19.92	1.48	9.85	0.14	7.12	7.66	3.38	0.35	0.06	99.11	53.2
J9-48	Y	52.76	1.75	18.81	1.70	11.30	0.10	4.38	3.07	2.92	2.15	0.22	99.19	37.8

Analyses performed by XRF in the Department of Geology, Macalester College, St. Paul.

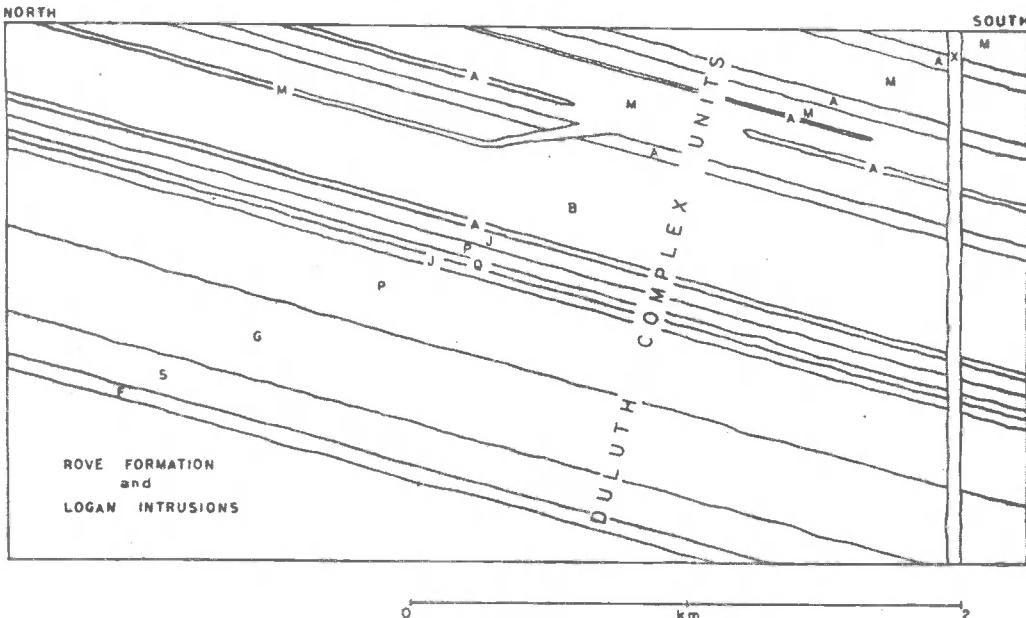


Fig. 1. North-South cross section of the Early Gabbroic Series. Note the P-J-Q-P-J sequence in the center of the figure. (from Nathan, 1969).

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GEOPHYSICAL ANSWERS TO GEOLOGIC QUERIES IN THE SUPERIOR PROVINCE OF NORTHERN MINNESOTA

JIRSA, Mark A., and CHANDLER, Val W.

(Minnesota Geological Survey, jirsa001@umn.edu, and chand004@umn.edu)

Geophysical investigations play a vital role in geologic mapping in Minnesota. As an example, we present here some highlights from mapping the Archean Superior Province in parts of Minnesota where the bedrock is covered by glacial sediment as thick as one hundred meters. Mapping of the well-exposed Archean rocks, restricted largely to the Vermilion district of northeastern Minnesota (Fig. 1), was completed in the 1960s and 1970s. Although significant, this outcrop mapping suffered from two shortcomings: 1) the area constitutes less than 5 percent of the state's bedrock crust; and 2) the Vermilion district may not be representative of the remainder of the state's Archean terranes that comprise two-thirds of Minnesota's first crystalline bedrock beneath glacial materials. These shortcomings were recognized in the late-1970s by Dr. Matt Walton, then-director of the Minnesota Geological Survey (MGS). He lobbied the State Legislature and received funding (from 1979 to 1991) to collect high-resolution, state-wide, aeromagnetic data. Additional aeromagnetic data were contributed by the U.S. Geological Survey and U.S. Steel Corporation. This was coupled with efforts to map areas having poorly exposed bedrock, acquire gravity and corresponding rock properties data, and drill test-borings in locations determined by the new geophysical data and geologic models. After two decades, the results include aeromagnetic coverage of the entire state, a grid containing more than 56,000 gravity stations (averaging 1 station per 2 square kilometers, state-wide), 2,500 determinations of density and magnetic susceptibility from nearly every major rock type, and drill cores representing many of Minnesota's Archean rocks. Armed with these data, the MGS has produced variably detailed geologic maps, and in the process raised important questions about the nature of the Archean crust. Some of those questions are described below.

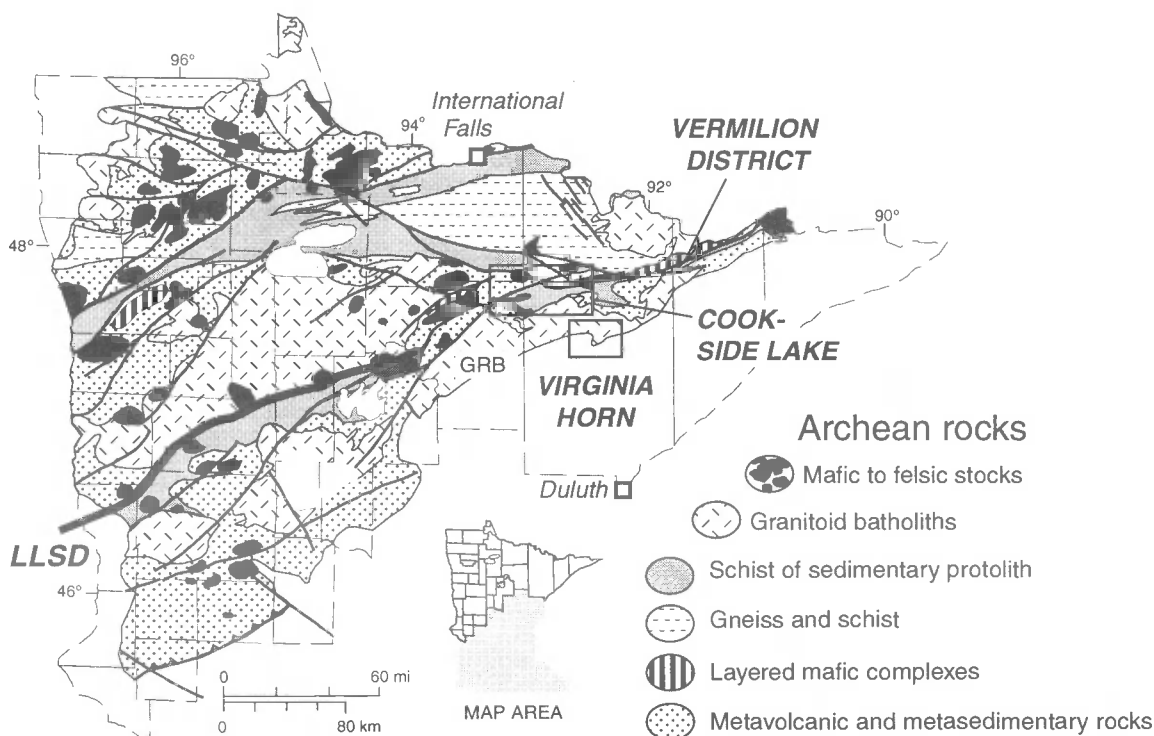


Figure 1. Simplified geologic map of the Superior Province in Minnesota showing the location of various map areas discussed in the text (LLSD—Leech Lake structural discontinuity, GRB—Giants Range batholith).

Early thrust nappes

Mapping in the Cook-Side Lake area (Fig. 1) was directed toward understanding the geological relationships between well exposed strata of the Vermilion district on the east, and the less well exposed rocks of the Side Lake area on the west. The volcanic sequences in each district are lithologically similar, and form broad anticlines that face stratigraphically toward one another. The intervening area, covering some 600 square kilometers, is marked by scattered exposures composed of turbiditic graywacke and slate of the Lake Vermilion Formation. These strata are complexly deformed, and their interpretation required detailed structural and sedimentological analysis. The model that evolved requires that much of the Lake Vermilion Formation has been exhumed to a level that exposes the bottom of a very large thrust nappe. Geophysical data are consistent with this interpretation, as they show graywacke as a relatively thin, geophysically translucent package overlying a "floor" of denser and variably magnetic volcanic strata.

Leech Lake structural discontinuity

The broadly folded volcanic and turbiditic strata of the Lake Vermilion Formation are part of what is known as the Soudan belt. The Soudan belt is structurally contrasted with the adjacent Newton belt to the north; the latter forms a series of fault-bounded, mostly north-facing, homoclinal panels. The Newton belt differs further in containing komatiitic flows and abundant mafic to ultramafic sills that are not present in rocks of the Soudan belt. In the well-exposed Vermilion district, the belts are dissected by late faults to such an extent that the relationships between the belts, and even the exact position of the boundary, are unclear. Extending the belts westward away from the zone of coinciding faults using a combination of geophysical, outcrop, and drilling data identified a major state-wide discontinuity between the two contrasting structural panels. Although its origin is not well understood, the informally named Leech Lake structural discontinuity (LLSD on Fig. 1) is considered a significant Archean crustal suture.

Mud Lake syncline

Because Archean bedrock in the area known as the Virginia horn (Fig. 1) is mantled by magnetic iron-formation of Paleoproterozoic age, recent mapping in the area relied almost exclusively on gravity modeling. The Archean bedrock is marked by a large fold, thought by earlier geologists to be an anticline, having graywacke in the core and volcanic strata on the limbs. The graywacke is complexly folded, and detailed structural analyses of cleavage/bedding relationships produced a contrasting model of an early-formed, west-facing, upright syncline. The model was tested by a series of gravity profiles that outlined a broad synform that is cored by relatively low-density graywacke, and flanked by inward-facing limbs of dense basaltic crust. Gravity modeling indicates that graywacke along the syncline axis is 1 to 2 kilometers thick and underlain by dense basaltic rocks.

Geophysical boundary at 5 kilometers

Constrained by physical property data, gravity and magnetic model studies of Superior Province rocks in Minnesota indicate that density and magnetization contrasts associated with the Archean greenstone-granite belts do not appear to extend to depths much greater than about 5 kilometers. This depth is surprisingly shallow, given the width and near-vertical geometry of most of these belts. The belts could be cut off by low-angle thrusting, which would be consistent with the convergent-margin, accretionary models advanced by the Canadian Lithoprobe project. On the other hand, the limited depth extent of the greenstone-granite belts could represent enhanced assimilation and mixing of magmatic and supracrustal components at depth. Support for the latter model exists along the southern boundary of the Giants Range batholith with adjacent supracrustal sequences that are complexly invaded and locally migmatized by granodiorite. In either interpretation (low-angle thrust or assimilation at depth), gravity and magnetic model studies indicate the observed anomaly signatures associated with Superior Province rocks in Minnesota are largely the result of sources within the uppermost crust, and that relatively little anomaly signature is apparently produced by middle or lower crustal rocks.

In summary, aeromagnetic data, supplemented by gravity and rock property data, have had tremendous impact on mapping Superior Province rocks in Minnesota. These geophysical data provide an essential framework and continuity that is not typically available from existing drill holes and outcrops. During the last 20 years, much of the Archean bedrock outside of the Vermilion district has been remapped at scales of 1:1,000,000 or greater. This ongoing mapping provides a valuable base for launching mineral exploration programs, and has revolutionized our understanding of early crustal evolution in Minnesota.

DISTRIBUTION OF ARSENIC IN WISCONSIN GROUNDWATER

DAVE JOHNSON, Drinking Water & Groundwater Bureau, Wisconsin Department of Natural Resources, PO Box 7921, Madison, WI 53707-7921,
johnsdm@mail01.dnr.state.wi.us

In the past ten years, with the recognition of elevated arsenic in drinking water supplies, the Wisconsin Department of Natural Resources has analyzed over 15,000 individual samples statewide. Ten percent of the statewide samples exceed the 10 ppb proposed Arsenic standard by the US Environmental Protection Agency; in some large areas over 25 percent of the samples exceed this level. The objectives of the sampling program were to (1) identify the distribution of elevated arsenic in water supplies, (2) identify concentration ranges and causes for the elevated arsenic, and (3) determine construction guidelines to minimize the problem.

The arsenic appears in many settings, the most common presently recognized being a northeast trending belt in east-central Wisconsin, west of the Fox River. The highest concentration in Wisconsin, 15,000 ppb, occurs in this belt. Numerous studies (Burkel, 1993; Pelczar, 1996; Simo and others, 1996, 1997; and Gotkowitz, 2001) have identified a sulfide-rich horizon recognized near the top of the St. Peter sandstone. This appears to be the principal source for As in this area. However, there are some elevated levels west of the western-most subcrop extent of the sandstone unit.

Other areas of elevated As have been identified. These include relatively shallow domestic water wells in Silurian dolomite in southeast Wisconsin and in association with the Upper Mississippi Valley Zinc-Lead District in southwestern Wisconsin. Elevated concentrations are also noted in isolated areas in central and northeastern Wisconsin associated with unique Precambrian units.

Township-based surveys of private wells in east central Wisconsin are continuing and may permit greater delineation of the As problem and possible solutions.

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FLUID INCLUSION EVIDENCE FOR A ROLE FOR HYDROTHERMAL ACTIVITY IN THE ROBY ZONE, LAC DES ILES MINE, NORTHWESTERN ONTARIO

JOHNSON, J.R. and KISSIN, S.A., Department of Geology, Lakehead University, Thunder Bay, ON, P7B 5E1, stephen.kissin@lakeheadu.ca

The Roby Zone of the Lac des Iles Pd-Pt-Ni-Cu-Au mine, located 90 km north-northwest of Thunder Bay, Ontario, was the initial locus of mining activity in the deposit. A striking aspect of the deposit in the early stages of mining was the coincidence of the ore zone with an envelope of talcose hydrothermal alteration (Michaud, 1998). Based on evidence of hydrothermal activity in off-set and deep, copper-rich deposits at Sudbury (Molnar et al., 1997) and observations of felsic veins and pods in the Roby Zone, an investigation of fluid inclusions was undertaken.

From a suite of samples collected during pre- and early-mining stages at the Roby Zone by Michaud (1998), hand specimen were selected. The hand samples used in the study were selected based on the presence and abundance of transparent minerals.

From three hand samples (Lac-318, Lac-304 and Lac-46) taken from the heterolithic gabbro located in the middle of the Roby Zone, a number of doubly polished sections 100 μm -thick were prepared. Sample Lac-318 is composed of pegmatitic gabbro that contain minor veins of plagioclase and epidote. Sample Lac-304 consists of a quartz vein that is emplaced within a medium-grained gabbro. The last sample used, Lac-46, is a medium-grained gabbro crosscut by a felsic vein network.

Four distinct types of fluid inclusions were observed occurring in plagioclase and quartz:

Type I - Single-phase liquid inclusions. These were extremely numerous in quartz but less common in plagioclase.

Type II - Two-phase inclusions (liquid + vapour). The most numerous type of inclusion that was found in plagioclase. The majority had a vapour content of 10-20% by volume.

Type III - Polyphase inclusions (liquid + vapour + one or more solid phases). These were fairly abundant but of a small size, occurring only in plagioclase. Numerous inclusions contained a single crystal, but only a few were found to contain more than one solid.

Type IV - CO_2 -rich polyphase inclusions. These were found only in plagioclase, containing two solids, two liquids and vapour.

The fluid inclusion studies revealed the following results:

Type II and Type III inclusions - All but one inclusion homogenized to vapour in the range of 540.1-352.4°C, but the majority were in the range 460-420°C. Eutectic temperatures generally clustered about -52°C or -49.8°C, the eutectics

for NaCl-CaCl₂-H₂O and CaCl₂-H₂O, respectively. Some lower eutectic temperatures observed may be the result of the small size of the inclusions and difficulty in detecting the first melting. Some eutectic temperatures were near -21.2°C, the NaCl-H₂O eutectic temperature. These may be attributed to lower concentrations of CaCl₂, such that its effects on melting behaviour were difficult to observe. Most inclusions in this group had final melting temperature of about -20°C, indicating moderate to high salinity.

Type IV inclusion - Only one inclusion containing liquid CO₂ and two daughter crystals was observed. The eutectic temperature was -54.2°C with a final melting temperature of -15.5°C, consistent with data from Type II and II inclusions. Liquid CO₂ homogenized to vapour at 26.8°C, and the remaining vapour homogenized to liquid at 160.8°C. However, the daughter crystals melted at 230°C and >412°C, the decrepitation temperature.

Type I - Liquid only inclusions exhibited eutectic temperatures of ~-34°C and final melting temperatures of ~-15°C. These inclusions, although saline, were clearly formed at low temperature.

The study has shown that high-temperature saline fluids are intimately associated with the ore zone of the Roby Zone. It is suggested that the present distribution of the ore is the result of hydrothermal activity associated with these fluids, possible of late magmatic origin. Similarity to fluids active in the Sudbury Igneous Complex is striking.

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HYDROGEOCHEMICAL MODELING OF ARSENIC IN MINNESOTA GROUND WATER

KANIVETSKY, Roman, Minnesota Geological Survey, 2642 University Avenue, St. Paul, MN 55114, kaniv001@umn.edu

Concentrations of dissolved arsenic in Minnesota ground water commonly exceed $3\mu\text{L}$ (micrograms per liter) and are as much as $157\mu\text{L}$. The highest regional concentration of arsenic in ground water ($0.06\text{--}91\mu\text{L}$, mean $6\mu\text{L}$) is documented in the western part of the state where the aquifers are buried bodies of sand, gravel, and silty sand that form discontinuous lenses beneath lake deposits and within till. Because of this, the hydrogeochemical modeling was performed for ground water systems in this part of the state.

A surface complexation two-layer sorption model was used to assess the mechanisms controlling arsenic distribution in the Quaternary buried artesian aquifer and Cretaceous aquifer systems. The release of sorbed arsenic from iron hydroxides into ground water was estimated by this model. The test data consisted of concentrations of total arsenic and iron in solution; this was derived from the arsenic and iron concentrations in the geological materials. The result of this model is the distribution of arsenic—either adsorbed to the surface of iron hydroxides, or into the aqueous phase.

These results suggest that mobility of arsenic is promoted by the onset of suboxic conditions in aquifer systems where iron hydroxides have sorbed arsenic. The reduction of ferric oxides and hydroxides, together with the reduction of As(V) to the less-strongly adsorbed and more mobile As(III), can release adsorbed arsenic into ground water. This reduction may be driven by microbial degradation of natural organic matter in aquifer systems. The source of the arsenic in the Quaternary buried artesian system is presumed to be iron oxides and iron hydroxides that have sorbed arsenic, and form amorphous coatings on mineral grains within the silty-clayey till. Despite the fact that the arsenic concentrations in the ground water and the geological materials used for the modeling were far apart, the modeling illustrates that the process is probably generic and not limited by geography.

Based on the sorption model and the classification of aqueous environments, the working model that explains the mechanisms controlling distribution of arsenic in ground water can be applied to five hydrogeochemical systems in Minnesota: the Quaternary buried artesian aquifer system, the Quaternary water-table aquifer system, the Cretaceous aquifer system, the Paleozoic-Mesoproterozoic artesian basin aquifer system, and the Precambrian crystalline rock aquifer system. The thick, silty-clayey, glacial and lacustrine sediments that cover the aquifers of the Quaternary buried artesian aquifer system in west-central Minnesota serve as a geochemical transition zone associated with the transformation from oxic to suboxic conditions. In areas where the till is more sandy, suboxic conditions may not exist. Variability in arsenic concentrations in water of the Quaternary buried artesian aquifer system can thus be explained by changes in geochemical conditions, the variability of the arsenic content in the sediments, or by variability in distribution of chemical reductants (e.g. buried organic matter). Waters within other hydrogeochemical systems typically have low concentrations of arsenic, possibly because they are associated with oxic conditions. High arsenic concentrations associated with sulfide mineralization or iron-formation may be present locally within any system, but are not a regional feature of any of these hydrogeochemical systems.

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ROCK MAGNETIC STUDIES OF PHYLLITIC ZONES FROM THE BARABOO SYNCLINE, WISCONSIN.

KELLY*, COLLEEN, AND KEAN, WILLIAM F., Department of Geosciences,
University of Wisconsin –Milwaukee, P.O. Box 413, Milwaukee, WI 53201
wkean@uwm.edu. (* student)

Preliminary paleomagnetic results based on limited sampling from a variety of rock types, suggested that the magnetism of the metamorphic rocks associated with the Baraboo Syncline was pre-folding (Kean and Mercer, 1986). The detailed work by Mercer (1984) based on data from two quartzite sites on the southern limb and one site on the northern limb shows the magnetism is carried by hematite, and is pre-folding. The unfolded magnetic direction is Dec=201°, Inc.=66.4°, Alpha 95=10.7°, which gives a paleopole at 257° E, 4.67° N. This is consistent with 1.75Ga. paleopole positions for North American.

However, the sites with phyllites were notably inconclusive (Mercer, 1984). Possible causes are; incomplete structural information, synfolding magnetization that was not recorded by the quartzite, or anisotropy of magnetization caused during the folding. Nonetheless magnetic results from these strata could provide important clues about the actual age of folding of the syncline. The phyllites result from metamorphism of clay rich layers within the original sandstone sequence, which could also contain hematite, magnetite or maghemite. It is likely that the magnetic mineralogy, and/or the magnetic direction in these layers will change during metamorphism and folding, and therefore provide information on the deformation history.

A suite of oriented hand samples, collected from phyllitic zones on both sides of the Baraboo Syncline, were subjected to a variety of magnetic measurements to determine the magnetic mineralogy and remanent directions. The measurements included stepwise alternating field (AF) and thermal demagnetization to either 100mT or 750° C respectively, magnetic susceptibility, saturation isothermal remanent magnetization (SIRM), and hysteresis properties. A.F. demagnetization was mostly ineffective. However, the thermal demagnetization results show that the majority of samples have a single magnetic direction that reduced to zero intensity between 650-750° C. The SIRM plots never reach saturation by 300mT, and the coercivity of remanence (Hcr) values derived from the hysteresis loops are in the range of 140-180 mT. These results are indicative of hematite with an effective grain size of 15-20 µm, that probably developed during metamorphism. However, additional studies are required to exclude the possibility that the differences in the magnetic directions for these sites are not due to local structural conditions, or anisotropy of remanent magnetization.

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HEALTH SURVEILLANCE IN A COMMUNITY AFFECTED BY ARSENIC-CONTAMINATED WATER

Lynda Knobeloch and Charles Warzecha, Wisconsin Department of Health and Family Services
Shelli Nelson, University of Wisconsin-Madison, Environmental Toxicology Center

Many private drinking water wells in Wisconsin's Fox River Valley contain naturally occurring arsenic at levels of health concern (Riewe et al., 2000). In 1993, the Department of Health and Family Services surveyed water use and health status among families living in the affected region. Data from this initiative indicated that residents whose daily arsenic intakes exceeded 50 µg were approximately three times more likely to report skin cancer than residents with lower arsenic intakes (Haupt et al, 1996). The Department is currently re-evaluating arsenic exposure and health status in this region. Three factors make this re-evaluation timely. In January, the U.S. EPA lowered the safe drinking water standard for arsenic from 50 ug/L to 10 ug/L, increasing the number of wells that will be deemed "unsafe." Since the previous study, the number of families that use private wells in this region has increased dramatically. In addition, repeated sampling of several wells in this region seems to indicate that arsenic concentrations are increasing over time, possibly due to regional drawdown of the aquifer. The current study covers a much broader geographic region than the 1993 study. Each township within Outagamie and Winnebago Counties has been encouraged to participate. To date, nearly 2000 families have submitted well water samples for arsenic analysis and completed a 4-page health questionnaire. This larger study population, combined with a more extensive list of health outcomes, is expected to provide us with a better understanding of arsenic exposure and its impact on the health of families that consume water from private wells in these counties.

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HYDROGEOLOGIC SETTING OF ELEVATED ARSENIC IN SOUTHEASTERN MICHIGAN

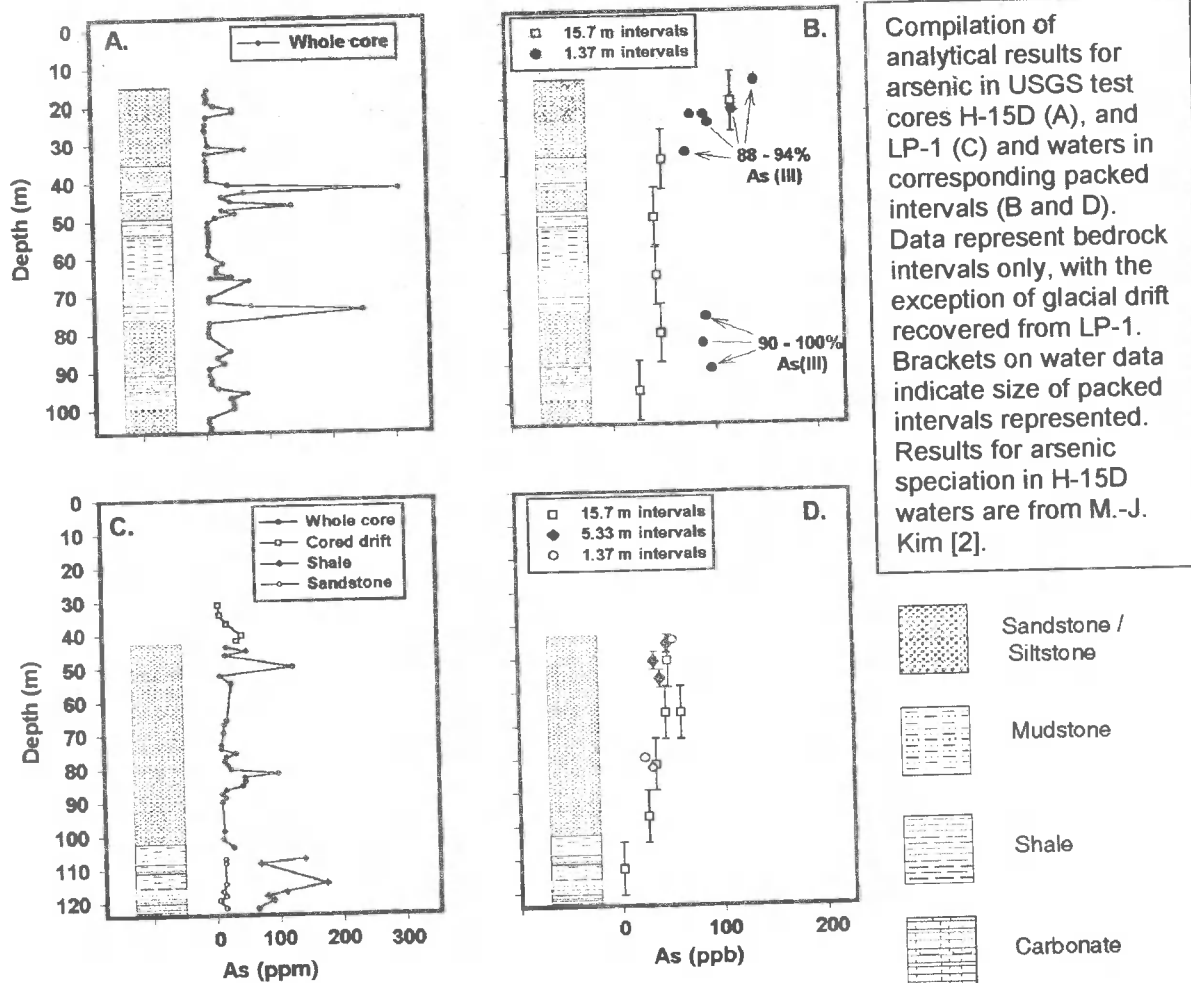
KOLKER, Allan, and CANNON, W. F., U.S. Geological Survey, Reston, VA, 20192,
HAACK, S. K., and WESTJOHN, D. B., U.S. Geological Survey, Lansing, MI, 48911, and
WOODRUFF, L. G., U.S. Geological Survey, Saint Paul, MN 55112.

High levels of arsenic, up to nearly 40 times the EPA standard of 10 $\mu\text{g/L}$, are present in southeastern Michigan, primarily in private supply wells. To investigate the problem, the USGS, in collaboration with the University of Michigan, sampled more than 100 wells, including public, private and monitoring wells, and examined aquifer materials in the region for possible sources of arsenic. The study area includes nearly all of Genesee, Huron, Lapeer, Livingston, Oakland, Sanilac, Shiawassee, Tuscola, and Washtenaw counties, which have a combined population of more than 2 million. Of the wells sampled by the USGS, more than 50% exceed the current EPA drinking water standard [1,2]. Most of the affected wells are completed in the Marshall Sandstone (Mississippian), the principal bedrock aquifer in the region, but in some cases, water in overlying glacial aquifers, or in the Saginaw (Pennsylvanian) aquifer is also affected. Problem wells are concentrated in the eastern and southeastern parts of the Marshall Sandstone subcrop belt, where Marshall Sandstone is in direct hydrologic contact with permeable Pleistocene glacial deposits [3].

To investigate the possible relation between the composition of aquifer materials and the arsenic content of well water, test wells were drilled by the USGS in Huron County (H-15D) and Lapeer County (LP-1), in areas known to contain wells with high arsenic contents. Both of the USGS wells show a gradual decrease in total arsenic of well water with depth, but redox conditions ($E_h = 29$ to 68 mV; [1]) and the fraction of As III (88 – 100% of total arsenic), measured for H-15D, are essentially uniform with depth (Figure). There is no distinct correlation between arsenic contents of aquifer materials, sampled in 4.5 ft. (1.37 m) intervals (0 to ~300 ppm), and waters, sampled largely in 50-ft. (15.7 m) intervals (Figure). Likewise, there is no correlation between As concentration and total Fe or SO_4 contents of waters in the region, even for samples having the highest (>50 $\mu\text{g/L}$) As contents. These findings suggest that in-situ pyrite oxidation in the Marshall aquifer is very limited.

In the Marshall Sandstone and in portions of the overlying Michigan Formation, pyrite is locally present as a cement whose texture indicates growth that has displaced framework sand grains. This pyrite locally contains highly arsenic-enriched domains (up to 8.5 wt. %) occurring as overgrowths on pyrite framboids having much lower arsenic contents, that are in turn incorporated into pyrite having low arsenic contents [4,5]. Well cuttings containing arsenic-rich pyrite have arsenic contents as high as 1020 ppm. Investigation of till samples containing iron oxy-hydroxides, probably derived from weathering of arsenian pyrite, shows arsenic contents up to about 0.7 weight percent. This indicates that a portion of the arsenic is retained during the weathering/oxidation process, or that arsenic is concentrated on oxide surfaces by adsorption of aqueous arsenic.

Because there are multiple sources of arsenic in glacial and bedrock aquifers that are in hydrologic continuity, no single process may explain the overall distribution of arsenic in southeastern Michigan wells. Reduction of iron-oxyhydroxides in glacial aquifers by exposure to suboxic ground water, is one possible source. In-situ pyrite oxidation, while limited, may locally be enhanced by high concentrations of bicarbonate [6]. Because of the extreme arsenic contents of some Marshall Sandstone pyrite, small amounts of in-situ oxidation could result in contamination of bedrock aquifers. Likewise, we cannot rule out sporadic paleo-oxidation of pyrite in the bedrock aquifer, resulting from lower water table levels that existed following the last glaciation. All of these processes have likely contributed to the widespread but sporadic nature of arsenic enrichment in southeastern Michigan ground water.



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POTENTIAL FOR COPPER MINERALIZATION IN THE ANIMIKIE GROUP, MINNESOTA

LARSON, Phillip C., Department of Geological Sciences, University of Minnesota, Duluth, MN 55812, plarson2@d.umn.edu

Numerous lines of evidence have recently been identified suggesting the potential occurrence of Keewenawan-style native copper or White Pine-style sediment-hosted copper mineralization in Animikie Group sediments in northeastern Minnesota.

Native copper has been reported in quartz veins in the Wanless Mine near Buhl (Gruner, 1946). Copper-stained rocks have been observed in the Butler Taconite mine (D. Ridgeway, pers. comm.). Hydrothermally altered diabase dikes in the National Steel Pellet Company (NPSC) Mine have elevated copper values (up to 950 ppm) associated with a chlorite-quartz alteration assemblage (Larson et al., 1999). In addition, diagenetic pyrite from the NPSC mine frequently displays a secondary coating of chalcopyrite on bedding and fracture surfaces. Finds of float native copper in glacial drift have occasionally been reported in the Nashwauk-Keewatin area of the Mesabi Range (L. Mattson, pers. comm.). It is improbable that this float copper is derived from the Lake Superior basin, as surficial drift on the Mesabi has either a northwest or northeast provenance; this strongly suggests a local provenance. These occurrences suggest the northern flank of the Animikie Basin has hosted a regional-scale mineralizing event by an oxidized cupriferous fluid.

The timing of copper mineralization is constrained by cross-cutting relationships. A series of diabase dikes intrude iron formation in the NPSC mine area; these dikes are tentatively dated at ~1100 Ma. Overprinting of alteration on well-developed cooling structures and post-emplacement shears in the dikes suggests that the copper mineralizing event significantly post-dated dike emplacement – similar to native copper mineralization on the Keewenaw peninsula. In contrast, in the South Stevenson Mine a diabase dike intruded the natural iron-ore body, indicating dike emplacement post-dates natural iron-ore formation. These relationships demonstrate that the natural iron-ore forming hydrothermal event is distinct from, and preceded the copper mineralizing event.

Morey (1999) has presented a model for formation of natural iron ore deposits on the Mesabi by alteration of Biwabik iron-formation by a hydrothermal fluid generated deep in the Animikie basin. A topographically-driven regional hydraulic flow system was induced by recharge in a highland area bounding the southern end of the basin. Fluids evolved deep in the basin were driven through relatively permeable strata at the base of the Animikie Group (Pokegama Quartzite). These fluids leaked upward along fractures through the overlying iron-formation toward the margins of the basin.

Concentration of iron oxides in natural iron-ore deposits is chiefly a function of silica removal from unaltered iron-formation. Evidence suggests that this process extended down into the underlying Pokegama Quartzite as well. Holway (1956) reported that at the Auburn Mine, quartzite underlying the natural iron-ore was composed of friable sand from which the silica cement had been leached. In most exposures, the Pokegama Quartzite is a well-cemented low permeability rock. However, local desilicification associated with natural iron-ore formation has enhanced permeability along numerous fault- and fracture-hosted fluid pathways.

During formation of the Midcontinent Rift System, rift-filling volcanics, intrusives, and sediments truncated the southern margin of the Animikie basin. The base of the Animikie Group is thus presumably in contact with volcanic rocks in the deeper portions of the rift – the likely source of oxidized cupriferous brines associated with Keewenawan native copper mineralization. These same fluids may have been driven from the western flank of the rift into the basal portion of the Animikie Group (Fig. 1). Fluid flow would have been focused through the basal clastic units, and in particular along the preexisting desilicified faults and fractures. Overlying iron-formation and shale units would have served as effective aquitards.

Two scenarios for concentration of significant copper mineralization by cupriferous brines discharging along the northern margin of the basin present themselves (Fig. 2). High-porosity, high-permeability desilicified clastic sediments within the Pokegama Quartzite may be the host for native copper mineralization similar to that observed in brecciated flow-tops and conglomerate beds on the Keewenaw Peninsula. Interaction of the brines with the iron-sulfide-rich base of the Virginia Formation may have produced stratiform copper sulfide mineralization similar to that observed at the White Pine and Presque Isle deposits.

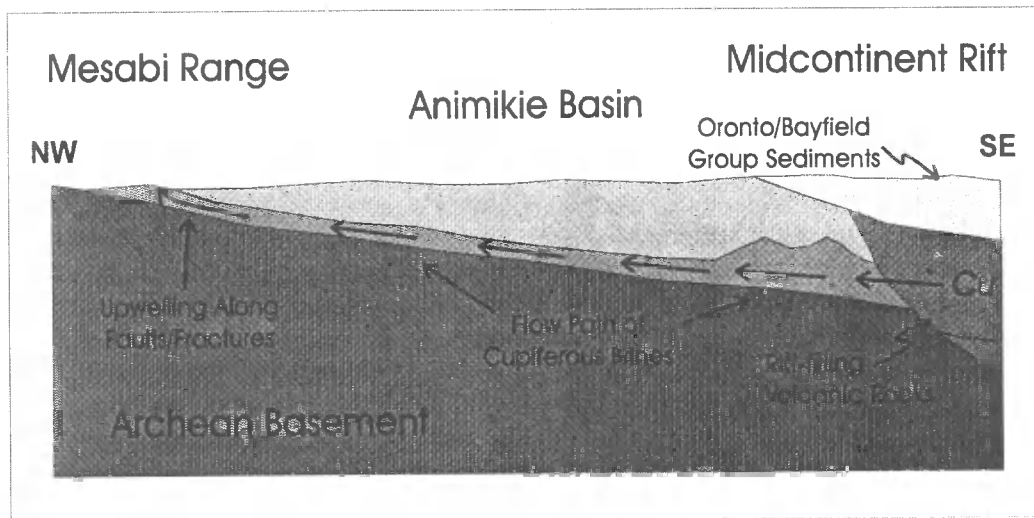


Figure 1. Schematic cross-section of post-Midcontinent Rift flow system through the Animikie Basin.

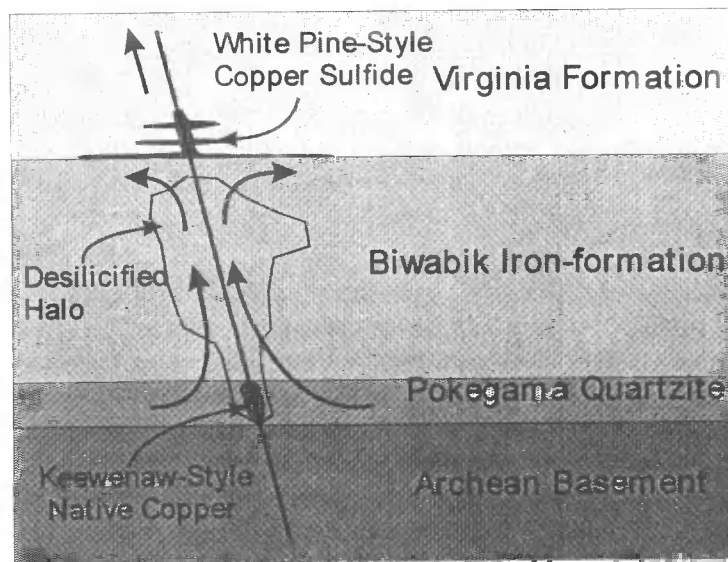


Figure 2. Schematic cross-section of copper mineralization, showing relationship between faults/fractures, desilicification, and Animikie Group sediments.

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CONTRIBUTIONS TO THE CULTURAL GEOGRAPHY OF THE WEST MESABI RANGE, NORTHERN MINNESOTA

LIVELY, Richard and MOREY, G. B.

(Minnesota Geological Survey, lively@umn.edu and morey001@umn.edu)

The Mesabi Iron Range in northern Minnesota has produced more than 4 billion tons of iron ore and taconite from more than 500 mines since ore was first shipped from that area in 1892. Mining, confined to an east-northeast trending strip of land some 100 miles long and 4 miles wide, has greatly modified both the original landscapes and associated cultural features. In this discussion, we assess some of those changes utilizing modern data and topographic maps prepared during the summer of 1899 and 1900 by E.C. Bebb and his assistants D.L. Fairchild and Louis B. Weed, all topographers with the U.S. Geological Survey. The original data were compiled at a scale of 1:16,000 with a contour interval of 20 feet, and ultimately were published at a scale of 1:50,000 in 1903 (Leith, 1903). The original field maps were obtained from the Cuyler Adams estate in the early 1980s and were subsequently digitized by Emily Bauer of the Minnesota Geological Survey to produce a pre-mining topographic rendition of the western half of the Mesabi range. The digitized maps were prepared as part of a larger study of the hydrologic character of the western Mesabi range sponsored by the Legislative Commission on Minnesota Resources (LCMR).

We compare here the 1899-1900 data with topographic data obtained in 1999 by the Minnesota Department of Natural Resources as part of the Mesabi Elevation Project (DNR, 1999). As one would expect, open-pit mining has considerably changed the topographic expression along the range, mainly by increasing the relative abundance and depth of topographically low areas and redistributing topographically high areas. In general, the overall spread in elevation has increased by over 100 feet due to excavation, while over the same period the maximum elevations on the range have not changed substantially. When comparing data from the 1999 high-resolution digital surface with data from the 1899-1900 survey in undisturbed areas, the resulting correlations are virtually identical. This implies a high degree of accuracy among the early topographers mapping the Mesabi range.

In 1899-1900, the western half of the range contained 11 mines and 17 mine dumps totaling about 0.7 square miles, or about 0.3 percent of the 230 square miles originally mapped. In 1986, mining activity accounted for about 140 square miles of pits and dumps, or about 60 percent of the study area. Mining also significantly affected drainage patterns along the range. In 1899-1900, mapped streams totaled over 400 miles in length, whereas only about 220 miles could be found compiled from topographic maps between 1970 and 1990, a reduction of about 45 percent. Much of that loss involved the removal of headwaters for many southward flowing streams along the south side of the Laurentian drainage divide.

The transportation features mapped on the range in 1899-1900 were primarily limited to about 170 miles of roads or trails and about 125 miles of railroad track. Most of these extended along the strike of the range, with relatively little development crossing the range. By 1990, railroad mileage had doubled to about 250 miles and road length had increased to over 1000 miles. In addition to the increased transportation network, mining created and destroyed many towns as it progressed. For example, the entire town of Hibbing was moved several miles after a rich deposit was discovered under its streets.

The Leith (1903) report also included a geologic map that was designed to aid exploration by delineating the boundaries of the Biwabik Iron Formation. That map, compiled during the spring of 1900 and the summers of 1900 and 1901, relied heavily on the support and geologic information, especially test pit and drill hole data, provided by J.U. Sebenius of the Lake Superior Consolidated Iron Mines (now owned by the U.S. Steel Corporation). Although the geologic data base was limited to relatively few, sparsely distributed data points, the resulting geologic map read very much as it does today, even with more complete data now available. The only significant difference involves a better understanding of faults and related structures which became apparent as extensive test drilling and mining progressed.

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PRECAMBRIAN GEOLOGY OF S. WISCONSIN: A PANORAMA FROM THE BARABOO RANGE
MEDARIS, L.G., Jr., Dept. of Geology & Geophysics, Univ. of Wisconsin-Madison,
1215 W. Dayton Street, Madison, WI, 53706, medaris@geology.wisc.edu

Red, supermature quartzites, most notably the Baraboo, Barron, and Sioux Quartzites, have long been recognized as a distinctive Proterozoic feature in the southern Lake Superior region, signifying deposition on a stable craton under conditions of intense chemical weathering in the presence of significant free atmospheric oxygen (Dalziel & Dott, 1970; Ojakangas & Weber, 1984; Southwick et al., 1986). The quartzites were inferred to be post-1750 Ma in age, to have been folded and metamorphosed at ~1630 Ma, and locally intruded by granitic rocks at ~1450 Ma. The term, *Baraboo interval*, was introduced by Dott (1983) for this succession of sedimentation, deformation, metamorphism, and intrusion in the time span of 1750 to 1450 Ma. In the last six years investigators at Wisconsin and Dan Holm at Ball State and coworkers have taken a renewed interest in the Baraboo interval, and their results substantiate the original concept and framework of the Baraboo interval and provide a more detailed understanding of the disparate geological processes that shaped the southern Lake Superior region in mid-Proterozoic time.

Igneous Basement of the Baraboo Range The Baraboo Quartzite is underlain by diorite, granite, and rhyolitic lavas and pyroclastic rocks (Dalziel and Dott, 1970). U-Pb zircon ages of the Baxter Hollow granite and rhyolite are indistinguishable, and taken together, yield an age of 1749 ± 12 Ma (Van Wyck, 1995). Chronologically and petrologically, the Baraboo basement is correlative with the subalkalic granite and rhyolite suite of the Fox River Valley (Smith, 1978; Anderson et al., 1980). Igneous textures are well preserved in all units of the Baraboo basement, although igneous minerals are partly to completely replaced by a variety of greenschist facies minerals. Typically, biotite is replaced by chlorite, plagioclase is transformed to albite and fine-grained epidote (saussurite), and intermediate alkali feldspar is recrystallized to a fine-grained mixture of near end-member microcline and albite. Hornblende in diorite is partly replaced by chlorite and intergrown actinolite and cummingtonite.

Paleosols beneath the Quartzites Mature paleosols have been recognized beneath the Sioux, Baraboo, and Barron quartzites (Southwick & Mosler, 1984; Medaris et al., 1997; Medaris, 2000). Among these paleosols, the Barron represents the best standard for comparison, because it has not been affected by later hydrothermal alteration, as have the other two. The Barron paleosol is a saprolite, derived from Penokean metatonalite and consisting of quartz, kaolinite, hematite, traces of sericite, and crandallite-florencite. During weathering of the metatonalite protolith, Al_2O_3 , TiO_2 and Zr remained immobile, Na_2O , CaO , MgO , and MnO were effectively removed, Ba, Sr, K_2O , and Rb were substantially reduced, and SiO_2 decreased by 10%. The extreme chemical maturity of the Barron saprolite is reflected in a high value, 95.7, for its Chemical Index of Alteration.

The Baraboo Quartzite is underlain by saprolite, which varies in thickness from 30 to 50 feet and was derived from granite and rhyolite. Chemical changes in the Baraboo saprolite relative to protolith are similar to those in the Barron, except for subsequent hydrothermal addition of K_2O and Rb.

Common features of the Barron, Baraboo, and Sioux paleosols are the absence of feldspar and a high degree of mineralogical and chemical maturity, similar to present-day weathering profiles in warm, humid climates, where intense chemical leaching is characteristic. Such a climate and a stable tectonic setting were essential for generating the supermature features of the Baraboo interval quartzites.

Depositional Age and Composition of Baraboo Interval Sedimentary Rocks A post-Penokean depositional age for the Baraboo interval quartzites was long recognized, and recent analyses of detrital zircon grains in the Baraboo, Barron, Flambeau, McCaslin, and Sioux quartzites have yielded numerous U-Pb ages from 1782 to 1712 Ma (Van Wyck, 1995; Dott et al., 1997; Holm et al., 1998), demonstrating that the quartzites were deposited no earlier than ~1710 Ma. The chemical maturity of the Baraboo

interval sediments was previously inferred from the near absence of detrital feldspar, the abundance of pyrophyllite or kaolinite, and the predominance of zircon, magnetite, rutile, and apatite among heavy minerals. Recent analyses of Barron, Baraboo, and Sioux siltstone, pelite, and their metamorphosed equivalents, yield compositions consisting essentially of SiO_2 , Al_2O_3 , Fe_2O_3 , TiO_2 , and H_2O , with a Chemical Index of Alteration ranging from 96.8 to 98.6. The extreme chemical maturity of the Baraboo interval sediments reflects a source region that experienced extensive chemical leaching and produced detritus consisting largely of quartz, kaolinite, and hematite.

1630 Ma Folding and Metamorphism There was widespread Rb-Sr isotopic resetting at 1635 ± 33 Ma in Fox River Valley granite and rhyolite, Baxter Hollow granite, and Baraboo rhyolite (Dott & Dalziel, 1972; Van Schmus et al., 1975; $\lambda = 1.42 \cdot 10^{-11} \text{ yr}^{-1}$), and it was suggested that such isotopic resetting was coincident with folding of the quartzites, which might represent an eastern expression of the Mazatzal deformation in the southwestern U.S. (Dott, 1983; Van Schmus et al., 1993). The extent of foreland deformation is marked by a 1630 Ma tectonic and thermal front in northern Wisconsin, which was located on the basis of $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages of mica and hornblende in basement rocks and the distribution of folding in quartzites (Holm et al., 1998; Romano et al., 2000).

The Barron Quartzite is unfolded and unmetamorphosed, consisting of quartz, kaolinite, and hematite. In contrast, the Baraboo Quartzite and underlying basement have been folded and recrystallized under low grade conditions (Medaris et al., 1998). The coexistence of quartz and pyrophyllite in the metasedimentary rocks requires a temperature between 285°C and 360°C , at 1 kbar and unit activity of H_2O .

Post-1630 Ma Hydrothermal Activity Muscovite grains from sub-Baraboo metasaprolite and from muscovite-pyrophyllite-diaspore veins near the base of the Baraboo quartzite yield discordant ^{39}Ar release spectra, with well-defined plateaux ages at 1456 ± 11 and 1467 ± 11 Ma, respectively (Naymark et al., 2001a). An apparent whole-rock Rb-Sr isochron age for saprolite and pedogene is 1336 ± 75 Ma. These data provide the first substantial evidence for a Wolf River-age imprint on the Baraboo Range, due to the effects of hydrothermal fluids that probably were driven along the sub-Baraboo nonconformity by heat from regionally extensive Wolf River magmatism.

Muscovite grains from two samples of Sioux pipestone, which contain the assemblage muscovite-pyrophyllite-diaspore, also yield discordant ^{39}Ar release spectra, but with significantly younger plateaux ages of 1370 ± 10 and 1268 ± 11 Ma (Naymark et al., 2001b). The geological significance of such ages is unclear at present, and the ~ 100 m.y. difference in ages of the two samples, which occur at the same stratigraphic level, deserves further investigation. Nevertheless, these recent $^{40}\text{Ar}/^{39}\text{Ar}$ results reveal the existence of important, and possibly widespread, post-1630 Ma hydrothermal activity in the southern Lake Superior region.

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RECENT ADVANCES IN UNDERSTANDING THE GLACIAL RECORD OF WISCONSIN

MICKELSON, D.M., Department of Geology and Geophysics, University of Wisconsin, Madison, WI 53706. Mickelson@geology.wisc.edu and CLAYTON, LEE, Wisconsin Geological and Natural History Survey, 3817 Mineral Point Rd., Madison, WI 53706.

Several glacier advances reached Wisconsin, but the record of early ice advances is sparse, probably because of their age (some >800 ka) and the intense erosion that took place during the subsequent glaciations (Alden, 1918; Bleuer, 1970; Baker, *et al.*, 1983; Miller, 2000). Thin, discontinuous till occurs on the uplands in west central and central Wisconsin and south of the late Wisconsin deposits in southern Wisconsin. Most have been classified into the lithostratigraphic system adopted by the Wisconsin Geological and Natural History Survey, as have younger glacial deposits (Mickelson, *et al.*, 1984; Attig, *et al.*, 1987; Clayton, *et al.*, 1991). More detailed mapping of Quaternary deposits at 1:100,00 scale has been published for about 18 counties, and several more are in preparation.

South and west of late Wisconsin and older glacial deposits lies the Driftless Area. Recognized as driftless since before 1850 because of its higher relief and lack of erratics, the Driftless Area has Paleozoic bedrock close to the surface with only a cover of loess less than 10m thick. The landscape has been produced by fluvial erosion since at least sometime in the Tertiary. Although Black (1960) suggested that it was glaciated, there is no evidence that it was (Mickelson *et al.*, 1982). In all likelihood, the Driftless Area remained unglaciated because it had to cross the deep, east-west Lake Superior basin. Much ice was diverted into the Green Bay Lobe and into the Superior Lobe, which extended westward into Minnesota. The Driftless Area is surrounded by glacial deposits of different ages, but was never surrounded by ice as portrayed by early workers and many textbooks.

Late Wisconsin ice advanced into the northeast Wisconsin by about 24,000 radiocarbon years ago based on model results and radiocarbon dates in Illinois. There is a relative lack of radiocarbon dates from this time period in Wisconsin, probably because permafrost was thick and tundra vegetation covered the landscape. Also, ice was particularly erosive behind the ice margin compared to further south in Illinois. Although there is no radiocarbon record of the advance, model results indicate that the Lake Michigan Lobe advanced more quickly than lobes that had to traverse the deep, east-west oriented Lake Superior basin (Cutler, *et al.*, 2000a) because extensive calving slowed their advance.

Ice of the Green Bay, Langlade, Chippewa, and Superior Lobes clearly advanced onto permafrost. This argument is based field observation of ice wedge casts (Clayton, *et al.*, 1997), the lack of buried wood, (Attig, *et al.*, 1989) evidence of tundra vegetation (Maher and Mickelson, 1996), and model results (Cutler, *et al.*, 2000b). Landforms near the maximum ice extent appear to reflect subglacial conditions at the time they were deposited. Relief within end moraines increases from about 10 m in southern Wisconsin to more than 60 m in northern Wisconsin, reflecting the wider, longer lasting frozen-bed zone near the margin. Drumlins are extensive, probably because slow melt out of subglacial permafrost caused inhomogeneities in the bed and differential streamlining. Tunnel channels left by large, probably catastrophic, flows of water from beneath the ice sheet are common along the outer margins (Clayton, *et al.*, 1999; Cutler, *et al.*, in press). Tunnel channels and drumlins appear to be absent farther south in Illinois where buried wood and model results indicate there were warmer temperatures during the advance to the maximum ice advance position.

The length of time that ice remained at or near the maximum position in the Green Bay lobe is debated. Maher and Mickelson (1996) have argued that ice remained near its maximum extent until about 15,000 years ago and that subsequent deglaciation was rapid based on radiocarbon dates from Devils Lake and northeastern Wisconsin. Colgan (1999; Colgan *et al.*, submitted) argue that deglaciation was slower based on cosmogenic dates and time needed for glacial landform development.

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THE DULUTH COMPLEX: WHAT IT IS, WHAT IT AIN'T, AND WHAT WE STILL DON'T KNOW

Miller, James D., Jr.

(Minnesota Geological Survey, c/o Natural Resources Research Institute, 5103 Miller Trunk Highway, Duluth, MN 55811 mille066@tc.umn.edu)

Since the time of the first Minnesota state geological survey over 100 years ago (1), several generations of geologists have worked to unravel the mysteries of the igneous rocks of northeastern Minnesota: the aptly named Duluth Complex. Each new level of understanding was brought about by new data or concepts about geological processes. With early survey studies recognizing the general distribution of igneous rock types, Grout's (2-5) work in the Duluth area established many of the broader geologic relationships of the Complex and developed fundamental concepts about how layered mafic intrusions form, many of which are still held today. However, one of his principle ideas, that the Duluth Complex is a large singular lopolithic intrusion (2), was proven to be an oversimplification by a flurry of geologic mapping conducted throughout the complex in the 1950s to 1970s (6-13). These studies were spurred by efforts to establish a geological framework within which to understand the Cu-Ni sulfide deposits first discovered in the late-1940s. Despite the fact that these deposits have yet to prove of economic importance, this intense period of geologic mapping served to formalize the general intrusive stratigraphy of the Duluth Complex and showed it to be a multiply intruded igneous system. In the early-70s, acceptance of the plate tectonic theory and recognition that the Duluth Complex was part of an intracontinental rift system created a new paradigm within which to evaluate the magmatic and tectonic history of the Duluth Complex (14).

The current generation of Duluth Complex studies have focused on five major objectives:

- 1) to interpret the geologic picture of the vast, poorly exposed central part of the Duluth Complex using high-resolution aeromagnetic data acquired in the early-1980s (15, 16);
- 2) to unravel the intrusive history of the complex with high resolution U-Pb dating of its gabbroic, anorthositic and felsic rocks (17, 18);
- 3) to delineate the internal igneous stratigraphy of the various layered intrusions of the Duluth Complex with core logging, detailed mapping, and petrologic studies (19-22);
- 4) to map the intrusive components of the hypabyssal Beaver Bay Complex and distinguish these from intrusions of the deeper Duluth Complex (23); and
- 5) to evaluate the potential for economic base- and precious-metal deposits in areas of known mineralization and in other unexplored areas of the Duluth Complex (25).

This presentation will highlight some of the new ideas that have emerged from this generation of studies and that are currently being summarized in a new 1:200,000-scale digital geologic map of northeastern Minnesota (see Miller and others, this volume) and in a companion report to be published in summer, 2001. It will also attempt to clarify some misconceptions about the Duluth Complex and point out where more study is needed.

Keweenawan intrusive igneous rocks compose more than 60 percent of the bedrock geology of northeastern Minnesota, but only about half of them constitute the Duluth Complex. The Duluth Complex refers to those intrusions that were emplaced into the base of the comagmatic volcanic edifice of the North Shore Volcanic Group. Intrusions emplaced higher within the volcanic pile are not considered part of the Duluth Complex, but rather belong to the Beaver Bay Complex or, where isolated, are identified as individual subvolcanic bodies. Other than scattered, isolated masses of strongly hornfelsed mafic volcanic rock, the Duluth Complex is virtually a continuous mass of intrusive igneous rock. Within that mass, four general rock series are distinguished on the basis of age, dominant lithology, internal structure, and structural position within the complex. Each rock series was multiply emplaced and, where possible, individual intrusion names are assigned.

Early Gabbroic Series—layered sequences of dominantly gabbroic cumulates occurring along the northeastern contact of the Duluth Complex. With their reversed magnetic polarity and 1108 Ma U-Pb zircon age (17), these rocks were evidently emplaced during the early magmatic stage of rifting. Two intrusive units are currently recognized: Nathan's Layered Series and the Cucumber Lake gabbro, though the latter has not been mapped in detail (10).

Felsic Series—massive granophyric granite with lesser intermediate rocks occur in a semicontinuous string of elliptical bodies along the eastern and central roof zone of the complex. Ongoing age dating and isotopic studies of these various bodies by Vervoort (26, 18) suggest that most were emplaced during early magmatic activity between 1109 to 1102 Ma and came from Paleoproterozoic to Mesoproterozoic crustal sources. The position of major mafic and anorthositic intrusions beneath these granophyre bodies suggests that the felsic rocks acted as density barriers to mafic magmas, thus causing their plutonic emplacement.

Anorthositic Series—a structurally complex suite of foliated, but rarely layered plagioclase-rich gabbroic cumulates that evidently formed by multiple emplacement of plagioclase crystal mushes (27). The erratic internal structure of these rocks typically precludes distinguishing individual intrusive bodies. Although commonly intruded by and included in layered series rocks, U-Pb dating indicates comparable ages of 1099 Ma for both rock series (17).

Layered Series—previously referred to as the troctolitic series (9-12, 14), this suite is composed of troctolitic to ferrogabbroic cumulates that constitute at least 11 major mafic layered intrusions. These intrusions display a range of internal differentiation from poorly differentiated troctolitic bodies, such as the Partridge River and South Kawishiwi intrusions, to the well-differentiated Duluth Layered Series and Greenwood Lake intrusion (21). Interpretations of geophysical data over the unexposed central and southern parts of the complex (15, 16; Miller and others, this volume) have led to the recognition of several previously unidentified layered intrusions: the Boulder Lake, Western Margin, Greenwood Lake, and Osier Lake intrusions. Aeromagnetic data also imply that emplacement of the thick sheet-like intrusions of the layered series occurred by sequential overplating of previous intrusions beginning in the northwestern part of the complex and progressing southeastward.

Although much has been learned about this enormous and complex igneous system in the past 20 years, much more remains to be done before a complete picture of the Duluth Complex is developed. Vast areas of the Duluth Complex and associated subvolcanic intrusions are unmapped in detail (especially in the BWCA). Age dating studies have only begun to unravel the emplacement history of Duluth Complex intrusions and their possible relationship to higher subvolcanic intrusions and volcanic rocks. Determining the igneous stratigraphy of the newly recognized, but poorly exposed layered intrusions (and their potential for stratiform PGE deposits) will require systematic drilling and geochemical studies. These and other challenges await the next generation of geologists who dare to tackle the mysteries of the Duluth Complex.

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DIGITAL GEOLOGIC MAP OF NORTHEASTERN MINNESOTA AND ASSOCIATED DATABASES IN GeMS—A MODIFIED ARCVIEW FORMAT

Miller, J.D., Jr.¹, Wahl, T.E.¹, Green, J.C.², Chandler, V.W.¹, Severson, M.A.³, and Peterson, D.E.^{2,3}

¹) Minnesota Geological Survey, 2642 University Ave., St. Paul, MN 55114; ²) Department of Geological Sciences, University of Minnesota–Duluth, Duluth, MN 55812; ³) Natural Resources Research Institute, 5013 Miller Trunk Highway, Duluth, MN 55811

The Minnesota Geological Survey (MGS), in collaboration with the Natural Resources Research Institute and the Department of Geological Sciences at the University of Minnesota–Duluth, is currently compiling geologic, structural, drill hole, geophysical and geochemical data from northeastern Minnesota into an ArcView-based GIS called GeMS (Geologic Mapping System). The main focus of this project, which is being funded by the Minnesota State Legislature through the Minerals Coordinating Committee, is to develop a new 1:200,000-scale geologic map of the Duluth Complex and related Keweenawan igneous rocks. The map will be available in summer, 2001 either as a 1:200,000-scale paper map, as a downloadable image from the MGS website, or as part of a CD-ROM that will also include all related data compiled for the study in an ArcView format. A companion report addressing the geology and mineral potential of the Duluth Complex will also be published in summer, 2001. This presentation will give an overview of the basic components of GeMS and will describe the types and attributes of database themes included in the compilation.

GeMS was initially conceived to be a user-friendly interface to the UNIX workstation-based ArcInfo software for the purpose of digitally storing, retrieving and imaging geologic, geophysical and geochemical data (Wahl and others, 1995, 1997). GeMS was recently converted to ArcView 3.2 for this and other MGS mapping projects because of ArcView's common usage as GIS software on the PC platform, its expanded data management capabilities, and its more flexible and easy-to-use graphical user interface. ArcView manages geographical data as point, line and polygon themes and links them to attribute tables containing related information. ArcView is particularly well-suited to making geologic maps because of its ability to sort data and interpretive themes by various attributes, to graphically portray the sorted data in a variety of ways, and to accommodate various types of base images (DRGS, geophysical images, orthophotos, etc.). The types of data and information themes that are part of the current version of GeMS are listed in Table 1.

Table 1. Data and interpretive themes included in GeMS

Data type	Theme type	Attributes
outcrop	polygon	field station ID, geologist, date visited, data source, observational detail, exposure, outcrop types, # of photos taken, # of samples taken, rock type, field description, map unit
sample	point	field station ID, geologist, date sampled, data source, form of sample, rock type, map unit, field description, # of thin sections, petrographic description, related data available (probe, whole rock, isotope, assay, geochron, rock properties)
structure	point	field station ID, geologist, date measured, data source, structure type, attitude, confidence level, # of averaged measurements, display scale
drill hole	point	drill hole ID, date drilled, logged by, date logged, lessee, elevation, azimuth, plunge, depth, depth to bedrock, first bedrock, last rock type, present core location, core diameter
map lines	line	geologist, date, basis 1, basis 2, line type (e.g., fault, contact, dike, fold axis, etc.)
map unit	polygon	geologist, date, basis 1, basis 2, map label, unit description
miscellaneous	varied	gossan zones, test pit locations, etc.

The advantages of moving from the old cartographic methods of making geologic maps to a GIS-based approach are numerous: GIS maps are easily updated as new data become available; several types of geologic data can be viewed at the same time; and different bases can be used. In addition to these advantages common to all GIS map systems, GeMS incorporates some other unique and useful features. These include source identification data (who, when and where). This is especially important for the compilation of the 1:200,000-scale geologic map of northeastern Minnesota, which compiles data and interpretations from various sources. Another important feature is the identification of the basis for geologic interpretations (map lines and units). For example, possible options for the basis for a fault interpretation are: topographic expression, inference from aeromagnetic data, geologic unit offset, air photo lineament, or local observation in outcrop.

The database for northeastern Minnesota available on CD-ROM will not be a complete compilation. The amount of detailed outcrop data alone that could potentially be compiled totals more than 100,000 polygons. This project is concentrating on data from areas that are open to mineral exploration. The completeness of the database at present is shown in Table 2. In addition to continuing to fill out this database, some other elements that will be added to GeMS include 1) compiling all geochemical data and linking that database to outcrop and drill hole samples, 2) allowing for drill core logs to be added to the database, and 3) exporting portions of the system to handheld devices to allow direct data capture in the field. As new mapping is conducted and new data are acquired, updated versions of the regional geologic map and its associated database will be published—a task made easier having moved our map-making into the digital age.

Table 2. Current Status of Data Compilation for the Northeastern Minnesota Geologic Map Area

Data Type	Total units to be compiled	Units compiled to date	Areas where compilation nearly complete	Areas yet to be compiled
Outcrop	>100,000	~23,000	Duluth area, southern and central Duluth complex, Allen and Babbitt quadrangles, Beaver Bay Complex ¹	Northern Duluth Complex (map areas of Phinney, Davidson, Foose, and Nathan), North Shore (Green)
Samples ²	~5000	~3600	Duluth area, central Duluth Complex, Allen quadrangle, Beaver Bay Complex	Samples of Green and misc. uncatalogued samples and thin sections stored at the MGS
Structure	~8000	>5000	All published geologic maps	Unpublished mapping by Phinney and Green
Drill Holes	~600	~600	All drill hole data are compiled	

¹) only about 30% of outcrop polygons in the Beaver Bay Complex have their attributes compiled, the unattributed polygons thus mark only outcrop location.

²) includes well-located samples for which geochemical, petrographic, or rock property data exist and/or for which a preserved sample or thin section exists.

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STRUCTURE OF THE BURIED PRECAMBRIAN BASEMENT IN SOUTHWEST WISCONSIN AND ITS INFLUENCE ON REGIONAL PALEOZOIC GEOLOGY AND ZINC-LEAD MINERALIZATION

MUDREY, M.G. Jr., Wisconsin Geological and Natural History Survey,
3817 Mineral Point Rd., Madison, WI 53705, mgmudrey@facstaff.wisc.edu
BROWN, B.A., Wisconsin Geological and Natural History Survey,
3817 Mineral Point Rd., Madison, WI 53705, babrown1@facstaff.wisc.edu

Our recent geologic mapping in southwestern Wisconsin has focused on pre-Sinnipee Group formations in the area north of the historic upper Mississippi Valley Zinc-Lead Mining District and south of the Wisconsin River. The regional stratigraphy can be clearly defined from outcrop exposures and mineral exploration boreholes in the Tunnel City Group, Trempealeau Group, Prairie du Chien Formation, and Ancell Group. The relatively easy recognition of the various units, in some cases to within 3 meters of a member or formation boundary, permits recognition of repeated sections and offset. This and previous mapping permits delineation of regionally significant anticlines, synclines, and faults, some which of have throws of more than 30 meters.

Our analysis of recent aeromagnetic data (Bracken and Nicholson, 2000) leads to a better understanding of folds and faults recognized in outcrop and permits extrapolation of some of the faults to the east at least 60 km. The large, broad folds mapped by previous workers were based on detailed examination of mineral exploration boreholes and outcrops. Many of the structures correlate with basement linear features defined from the aeromagnetic data. Some of the folds, such as the Allamakee Anticline, may be related to readjustments along Keweenawan and older structural features (such as the Belle Plaine Fault and equivalent structures). Other east-west features, notably the Meekers Grove Anticline, are coincident with aeromagnetic linears at depth. These linear features are probably faults or faults with coincident dikes and probably define the north tectonic edge of the Illinois Basin. Regional map analysis suggests a steepening of dip of the Paleozoic rock units southward into the Illinois Basin along these regional deep basement trends, from a regional dip of less than 10 feet per mile to over 20 feet per mile.

The large, quiet magnetic areas in western Grant County and else where in southern Wisconsin may reflect Wolf River-age plutons within the basement because the signatures are circular and apparently undeformed. Wolf River-aged material has been drilled along the state line between Wisconsin and Illinois (Coates, and others, 1983). Some of the linear anomalies defined from aeromagnetic data are coincident with positive linear gravity anomalies (Geister and Ervin, this meeting) and are probably wide, mafic dikes. The location of the plutons and faults probably influenced sedimentation patterns during the early Paleozoic by localizing the large reef/carbonate bank deposits of Middle Ordovician (Ludvigson and others, 1983).

It is commonly thought that deep brines from the Illinois Basin gave rise to the hydrothermal solutions responsible for mineralization (Bethke, 1986). Localization of the

zinc-lead mineralization along small faults and folds in mine workings is well documented from detailed mine mapping; however, this mineralization does not appear to be related to the deeper, more extensive basement structures. Heyl and others (1970) concluded that the broad-scale folds and faults were responsible for the tectonic framework, but the structures controlling ore deposition were developed by solution and slumping during the mineralization stages.

We propose that the broader tectonic elements at the periphery of the Illinois Basin controlled ascent of the hydrothermal brines and therefore distribution of regional mineralization. The rapid cooling of those ascending brines along fractures resulted in the mineral concentrations. In this model it is the details of depth of burial of individual geologic units, their uplift and cooling history, and timing of transit of the hydrothermal brines, that are important in mineralization rather than host-rock lithology and local structure.

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PRELIMINARY ANALYSIS OF AEROMAGNETIC DATA IN SOUTHERN WISCONSIN: THE ROLE OF PRECAMBRIAN BASEMENT IN PALEOZOIC EVOLUTION

MUDREY, M.G. Jr., Wisconsin Geological and Natural History Survey,
3817 Mineral Point Rd., Madison, WI 53705, mgmudrey@facstaff.wisc.edu
BROWN, B.A., Wisconsin Geological and Natural History Survey,
3817 Mineral Point Rd., Madison, WI 53705, babrown1@facstaff.wisc.edu
DANIELS, David L., U.S. Geological Survey, MS954 National Center,
Reston, VA 20192, dave@usgs.gov

The new aeromagnetic map of Wisconsin was the result of digitally blending the data from 22 surveys flown between 1948 and 1999. The most recent survey (74,000 line-kilometers), acquired by the U.S. Geological Survey, covers much of southern Wisconsin. The flight line data for four surveys acquired by the U.S. Geological Survey during the past 12 years have been released on CD-ROMs. These data were added to earlier U.S. Geological Survey surveys and 4 surveys acquired by Wisconsin Geological and Natural History Survey. Flight lines are 800m apart or less for 95% of the state, giving the aeromagnetic map nearly uniform specifications. All surveys were either flown at or continued to an elevation of 305m above terrain prior to assembling into a state grid. The data interval of the grid is 250 m.

In this presentation, we show a preliminary analysis of the aeromagnetic data south of 43.5°, for which there is little Precambrian information either from outcrop or cuttings from deep boreholes. The resulting aeromagnetic map of southern Wisconsin illustrates the structure of the Precambrian rock underlying Paleozoic and Pleistocene cover. The pattern generally represents a complex Precambrian terrane that may include middle Proterozoic granite-green stone terrace containing small, circular anomalies related to the Wolf River batholith. The dominant Precambrian bedrock in eastern Wisconsin is quartzite of the Baraboo type. This unit is generally magnetically transparent; as a result, the magnetic signature originates from rock of the basement to the quartzite. In places, notably Fond du Lac County, folding within some units in the quartzite sequence is evident and suggests interbedded slate and iron formation.

Other basement features include well defined faults in the Precambrian, some of which are clearly of Paleozoic age. In eastern Wisconsin the Waukesha and related faults define a basement terrace boundary, and in southern Wisconsin the Beloit and other faults define the northern edge of the Illinois Basin. The lack of relationship between the Upper Mississippi Valley Zinc-Lead District mineralization and Precambrian basement suggests a minor role for pre-Paleozoic elements during localization of the zinc-lead mineralization.

**MISSISSIPPI VALLEY-TYPE MINERALIZATION IN THE FOX RIVER VALLEY,
EASTERN WISCONSIN (*Modified from 42nd ILSG - Cable, Wisconsin, 1996*)**

MUDREY, M.G. Jr., Wisconsin Geological and Natural History Survey,
3817 Mineral Point Rd., Madison, WI 53705, mgmudrey@facstaff.wisc.edu
BROWN, B.A., Wisconsin Geological and Natural History Survey,
3817 Mineral Point Rd., Madison, WI 53705, babrown1@facstaff.wisc.edu
FREIBERG, P.G., Department of Geology and Geophysics 1215 W. Dayton St.,
Madison, WI 53706-1692,
SIMO, J.A., Department of Geology and Geophysics 1215 W. Dayton St.,
Madison, WI 53706-1692, simo@geology.wisc.edu

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

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

Economic concentrations of Mississippi Valley-type mineralization have not been found in Wisconsin outside of Grant, Iowa, and Lafayette Counties, but geologic logs of 16 mineral exploration holes and more than 600 water wells in eastern Wisconsin contain reports of minor mineralization. In addition, more than 100 occurrences of sulfide minerals have been reported from outcrops and quarries throughout southern and eastern Wisconsin (Brown and Maass, 1992). A fairly continuous horizon of sulfide mineralization has been observed in quarries and drill core from Kenosha to Green Bay. Mineralization within this horizon consists of sulfide-cemented sandstone and sulfide infills of vugs and molds of fossil. The principal concentration of mineralization has been observed at or near the top of the St. Peter sandstone, but scattered mineralization is known throughout the Paleozoic section in this region.

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OVERVIEW OF FIELD TRIP 2: UPPER MISSISSIPPI VALLEY - ZINC-LEAD DISTRICT, WISCONSIN

MUDREY, M.G., Jr., Wisconsin Geological and Natural History Survey, 3817 Mineral Point Road, Madison WI 535705, mgmudrey@facstaff.wisc.edu
HUNT, T.C., Director of the Reclamation Program, School of Agriculture, University of Wisconsin - Platteville, Platteville, WI 53818, huntt@am.uwplatt.edu
CZECHANSKI, M.L., Wisconsin Geological and Natural History Survey, 3817 Mineral Point Road, Madison WI 535705, mlczecha@facstaff.wisc.edu

First recovery of galena in the Driftless Region of Wisconsin, Illinois, Iowa and Minnesota was by native Americans for ornamentation about 1000 C.E. By 1690 Europeans recognized the lead deposits and began mining in what is now known as the Upper Mississippi Valley Zinc-Lead District. In the early 19th century, this was the premier lead mining district in North America. Numerous immigrant groups and developers were attracted to the area and the resulting population in flux played a major role in the eventual formation of the states of Illinois, Iowa, and Wisconsin.

Initial mineral development (late 18th and early 19th centuries) consisted of collecting surface occurrences of galena and digging down until the excavations became unstable (badger holes). Deeper mining techniques were initiated, but were hampered by inadequate dewatering techniques below the water table. By 1850 lead production had peaked. Metallurgical developments and techniques to dewater mines led to significant zinc production (zinc ore became abundant with depth), initially from smithsonite (dry bone) and since 1900 from sphalerite. Peak production years were 1917 and 1952. The last mine, Eagle-Picher's Shullsburg Mine, ceased production in 1978.

Since 1900, the U.S. Bureau of Mines, the U.S. Geological Survey, and the Wisconsin Geological and Natural History Survey have collected large amounts of information from the area including, detailed mine maps, drillhole locations, assay data, and geologic logs. This information is summarized in detailed geologic maps. Al Heyl and others (1959) summarized information up to 1950s in U.S. Geological Survey Professional Paper 309. Heyl and others (1970) prepared a shorter summary of Professional Paper 309 for the Geological Society of America Meeting in Milwaukee in 1970. In addition, a large number of detailed geologic maps were prepared for southwestern Wisconsin and adjoining Illinois and Iowa.

This area is the type-locality of the Upper Mississippi Valley Zinc-Lead mineralization. Warm (135 to 180 °C) mineral-bearing saline brines from the south (Illinois Basin) and southwest (Iowa Basin) are responsible for the mineralization. The bulk of the mineralization occurred in Middle Ordovician strata during the Permian/Pennsylvania. Dominant mineralization occurred in the Decorah shaly dolomite, with significant quantities of mineralization in the over- and under-lying dolomite strata. Deeper mineralization has not been significantly tested. Local ore controls include minor folds and faults. Mineralization occurs as replacement and breccia filling in vertical fractures and crevices (gash veins),

dipping fracture planes (pitches) and horizontal bedding planes (flats). Gash veins not uncommonly occur directly over the pitch and flat structures. There is a general vertical ore zonation with lead in the vertical veins and zinc concentrated in pitches and flats. Replacement and solution breccia are common, leading to some bonanza-type mineralization. Wall rock alteration is minimal, suggesting no widespread thermal events, but rather joint and fracture localization.

The field trip will examine the Potosi Hill Ordovician geologic exposure, where the entire section from the Ancell Group through the Sinnipee Group is exposed; the Platteville Mining Museum and Bevan Mine which illustrates the regional geology and historical mineral development techniques; Pendarvis State Historical Site which captures the 1830s spirit of mining;; and modern reclamation at the Shullsburg site, location of the last producing zinc mine in Wisconsin (1978).

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RECOGNITION OF POST-1630 MA FLUID-DRIVEN METAMORPHISM IN BARABOO INTERVAL QUARTZITES BY MEANS OF LASER PROBE $^{40}\text{Ar}/^{39}\text{Ar}$ GEOCHRONOLOGY

NAYMARK, ALISSA, SINGER, BRAD and MEDARIS, L.G., Jr., Department of Geology and Geophysics, Univ. of Wisconsin-Madison, 53706, anaymark@students.wisc.edu, bsinger@geology.wisc.edu, medaris@geology.wisc.edu.

The southern Lake Superior region experienced many transformations during Proterozoic time. Quartzites of the Baraboo interval, most notably the Baraboo, Barron, and Sioux, are known to have been deposited between ~1710 Ma and 1630 Ma on 1750 Ma and older igneous and metamorphic basement. Quartzites south of Holm et al.'s (1998) tectonic front were folded at ~1630 Ma and, presumably, subjected to low-grade metamorphism at the same time. The present investigation, using CO_2 laser probe $^{40}\text{Ar}/^{39}\text{Ar}$ incremental-heating methods, was undertaken to evaluate the timing and extent of low-grade metamorphism in Baraboo interval sedimentary rocks. Surprisingly, little evidence for 1630 Ma metamorphism was found in the analyzed samples; instead, a strong signature of post-1630 Ma hydrothermal activity was discovered in the Baraboo and Sioux quartzites.

The Baraboo Range: Age spectra for three muscovite samples are discordant in the low temperature gas steps, but gave similar plateau ages. The initial 30% of gas released typically gave apparent ages beginning at ~900 Ma in the vein material, and ~1200 Ma in the samples from Baxter Hollow, rising to concordant plateau ages for the last 70% of the gas released. Muscovite from hydrothermal muscovite-pyrophyllite-diaspore veins in the base of the Baraboo Quartzite yielded a plateau age of 1467 ± 10 Ma ($\pm 2\sigma$) [Figure 1A]. Samples of muscovite from metasaprolite at Baxter Hollow yielded plateau ages of 1456 ± 11 and 1461 ± 12 Ma [Figure 1B]. These data provide the first evidence that hydrothermal metamorphism coeval with the Wolf River Batholith affected rocks in the Baraboo Range. We propose that this hydrothermal activity was due to large-scale movement of fluids through the crust, driven by heat provided by Wolf River granitic magmatism. The Denzer diorite is a member of the ~1750 Ma igneous suite underlying the Baraboo Quartzite. It preserves an igneous texture, but was weakly recrystallized, presumably at 1630 Ma, with plagioclase partly replaced by albite and epidote, biotite altered to chlorite, and hornblende altered to actinolite, cummingtonite, and chlorite. Biotite from the Denzer diorite yielded a plateau age of 1746 ± 12 Ma [Figure 1D] that may reflect time since crystallization. In contrast, two samples of hornblende with intergrowths of actinolite, cummingtonite, and chlorite, yielded ages of 1596 ± 16 and 1427 ± 15 Ma, which represent partial and complete Ar resetting of what may have been a 1630 Ma metamorphic assemblage.

Sioux Quartzite: Numerous samples of fine-grained metasedimentary rocks (pipestone) were collected from Pipestone National Monument, SE Minnesota. They were analyzed optically and via electron microprobe, X-ray diffraction, and X-ray fluorescence to determine their mineralogical and chemical compositions. Most samples contain the assemblage: muscovite-pyrophyllite-diaspore, similar to pipestone and hydrothermal veins at Baraboo. Owing to the fine grain size (~20 μm), less than 0.01mg whole rock samples were prepared from the Sioux pipestone based on X-ray diffraction patterns indicating that muscovite was the only potassium bearing phase present. The samples with K_2O greater than 4.0 wt. % and more than 35% modal muscovite were chosen for the whole rock $^{40}\text{Ar}/^{39}\text{Ar}$ experiments. The plateau ages are slightly discordant at low and high temperature. However, 80% of the gas gave plateau ages of 1370 ± 10 and 1268 ± 10 Ma [Figure 1C], suggesting that post-1460 Ma hydrothermal activity affected the Sioux Quartzite. The geological significance of these ages from Sioux pipestone remains unclear, and the 100 million year difference in age between two samples from the same stratigraphic level is problematic. A possible explanation is differential loss of argon via diffusion from multiple small domains within the submicroscopic mica.

The Barron Quartzite: The Barron Quartzite, which is located north of Holm et al.'s (1998) inferred tectonic front, was unaffected by 1630 Ma folding and metamorphism, and consists

predominately of quartz, kaolinite, and hematite. Although muscovite is rare in the Barron sedimentary rocks, it was found immediately below the Barron Quartzite in a vein, which cuts metatonalite basement. Both the vein and metatonalite are now saprolites, having been weathered in Proterozoic time, and the muscovite is partly replaced by kaolinite. The muscovite yields a plateau age of 1808 ± 14 Ma, demonstrating that the Barron Quartzite and underlying basement were *not* affected by 1630 Ma folding and metamorphism, or by 1460 Ma hydrothermal activity.

Conclusions: $^{40}\text{Ar}/^{39}\text{Ar}$ analyses of Baraboo and Sioux samples that were affected by K-metasomatism, including Baraboo metasaprolite and hydrothermal veins and Sioux pipestone, revealed post-1630 Ma hydrothermal activity in the southern Lake Superior region. Hydrothermal fluids attending Wolf River magmatism exploited the nonconformity separating quartzites from underlying plutonic and metamorphic rocks. The muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages most likely record low temperature crystallization ($\sim 300^\circ\text{C}$) assemblages in metasaprolite, hydrothermal veins, and pipestone. Further investigation will be necessary to delineate the scale of this potentially regional fluid flow in the crust.

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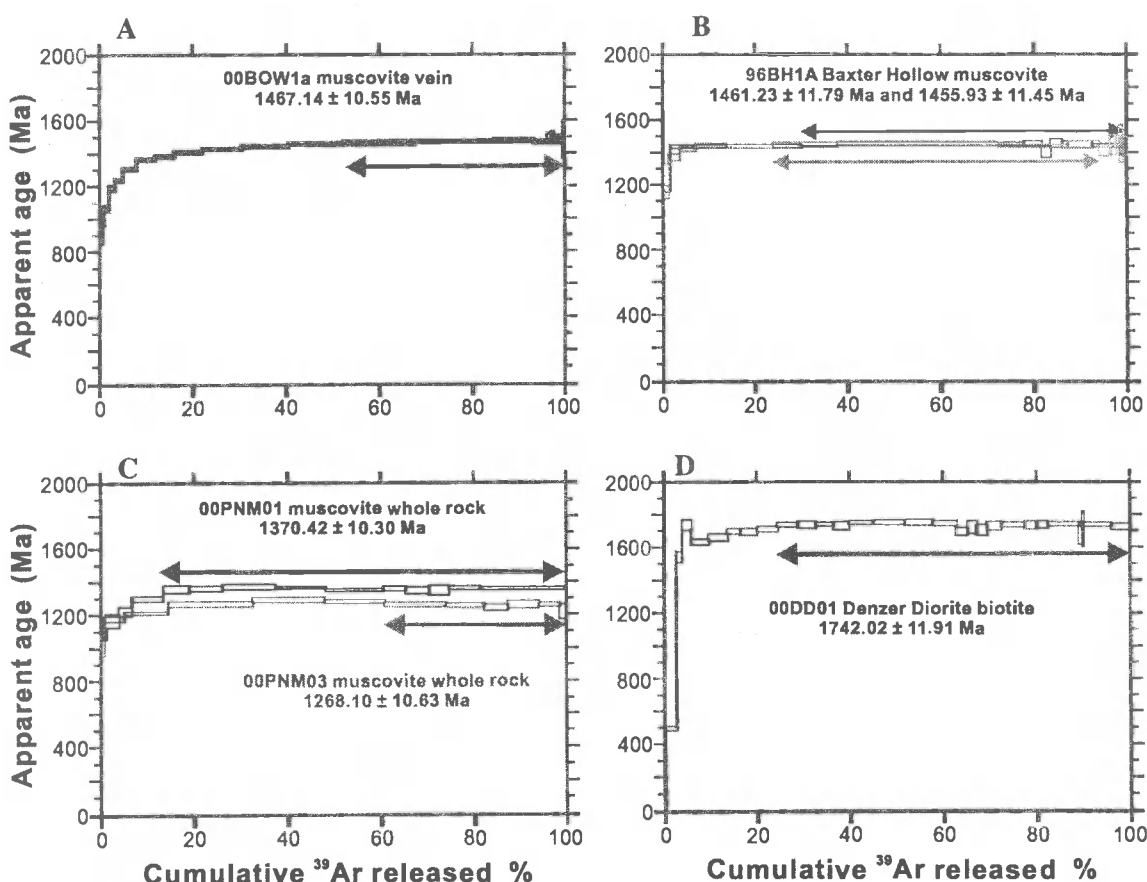


Figure 1: Age spectra discussed in text. Weighted mean plateau ages are reported with 2σ errors.

MINERALOGICAL VARIATIONS IN IRON-FORMATION IN THE THERMAL METAMORPHIC AUREOLE OF A DIABASE DIKE

NEMITZ, Michael B., and LARSON, Phillip C., Department of Geological Sciences, University of Minnesota, Duluth, MN 55812

The Biwabik Iron-formation in the National Steel Pellet Company Mine near Keewatin, Minnesota is cut by a series of diabase dikes. It has previously been empirically observed that iron-formation adjacent to these dikes is characterized by enhanced magnetite weight recovery, increased silica liberation indices, and increased oxidation reflected as elevated $\text{Fe}^{+3}/\text{Fe}^{+2}$ ratios.

Granular cherty iron-formation samples were collected in two transects perpendicular to the contact of a 5-m thick diabase dike. The transects extended 25-m along the strike of the iron-formation. Whole-rock geochemical analyses, x-ray diffractometry, and reflected- and transmitted-light polarizing microscopy were used to assess the geochemical, mineralogical, and textural variations in iron-formation adjacent to the dikes.

Microscopy indicates an increase in the total amount of primary, euhedral magnetite, hematite, and total Fe-oxide proximal to the dike. The total Fe-oxide content appears to increase in an exponential fashion. This trend is reflected in the whole-rock Fe content. Magnetite occurs in all samples as primary euhedral crystals. Hematite occurs in a number of forms: euhedral to subhedral pseudomorphs after magnetite (martite), as inclusions in the lattice of euhedral magnetite, or as fine grained aggregates.

Previous to iron-formation oxidation, a hydrothermal alteration event was focused along the dike margins. Alteration leached Mg, Ca, and Na from both diabase and iron-formation. This event is reflected in the iron-formation whole-rock Mg content, which show that Mg has essentially been removed in the 5-m zone proximal to the contact. Carbonate, and to a lesser extent Fe-silicate minerals have essentially been removed in the 10-m zone proximal to the dike contact. Conversely, void space is most abundant in this same zone. This suggests void space has been created at the expense of carbonate and silicate phases.

The increase in void space also correlates with the increase in hematite proximal to the dike. This suggests that the oxidation of Fe-oxides to hematite may be related to increased porosity and permeability of iron-formation due to void space. Increased porosity allowed oxidizing meteoric waters to circulate deeper along the dike margins.

This study demonstrates that thermal metamorphism of iron-formation by diabase dikes has caused an increase in Fe-oxide content, both magnetite and hematite, thus resulting in increased magnetite weight recovery. However, the increase in void space due to alteration has allowed increased circulation of meteoric waters, resulting in oxidation of iron-formation and elevated hematite content relative to magnetite.

PRELIMINARY LAVA FLOW MORPHOLOGY STUDIES AT THE FIVE MILE LAKE VMS PROSPECT, ARCHEAN VERMILION DISTRICT, NE MINNESOTA: IMPLICATIONS FOR VOLCANIC PROCESSES, VOLCANIC PALEOENVIRONMENTS, AND VMS EXPLORATION

TRENT T. NEWKIRK, GEORGE J. HUDAK

Department of Geology, University of Wisconsin Oshkosh, Oshkosh, WI 54901

STEVEN A. HAUCK

Natural Resources Research Institute, University of Minnesota-Duluth, Duluth, MN 55811

As part of a two-year grant from the Minerals Coordinating Committee (MCC, State of Minnesota), we have undertaken a field-based, detailed investigation of the pillow lava morphology at the Five Mile Lake volcanic-associated massive sulfide (VMS) prospect, which is located approximately 15 miles southwest of Ely, Minnesota. This prospect is situated within a greenschist facies metamorphosed assemblage of Archean subaqueous, primarily mafic metavolcanic and metasedimentary rocks. These rocks lie within the Lower Member of the Late Archean Ely Greenstone (Peterson and Jirsa, 1999).

Historically, several mineral exploration programs have been conducted in the Lower Member of the Ely Greenstone to evaluate its potential for VMS-style base metal mineralization. One of the most significant exploration programs to date was completed in 1995, when Teck Exploration Ltd. intersected stringer Zn-Cu mineralization in several diamond drill holes at the Five Mile Lake prospect.

Cas (1992) and Gibson et al. (1999) have emphasized the importance to mineral exploration programs of determining the volcanic environments associated with VMS mineralization. Gibson et al. (1999) have noted that mapping the orientation of synvolcanic dikes and sills is perhaps one of the most effective means to identify synvolcanic fault zones in lava flow dominated volcanic settings. This mapping is important because these structures not only dictate the location of volcanic vent sites, but also commonly control the locations of hydrothermal discharge sites responsible for making VMS deposits.

Unfortunately, the generally small size of synvolcanic dikes and sills relative to their volcanic products commonly makes them difficult to recognize, especially in ancient volcanic sequences that are often plagued by a general lack of outcrop. Thus, detailed facies mapping in volcanic sequences is also an essential part of determining vent proximal volcanic environments.

Studies of modern subaqueous mafic lava flows indicate that flow morphology has a direct relationship to effusion rate, cooling rate, and the slope upon which the lavas are erupted (Kennish and Lutz, 1998). In areas with relative fast effusion rates, sheet flows commonly occur in vent proximal environments, and grade laterally into pillow lavas farther from the volcanic vent. Slow effusion rates favor the immediate development of pillow lavas.

It is interesting to note that several studies (Ballard and Moore, 1977; Ballard et al., 1981; Hekinian, 1984; Hekinian et al., 1989) have found that the glassy margins on vent proximal sheet flows tend to be thicker than the glassy margins on more distal, pillow lavas formed from the same eruption. This occurs because pillow lavas generally contain more crystals or crystal nuclei that inhibit the formation of their glassy outer margins (Kennish and Lutz, 1998). Therefore, the thickness of the glassy margins on these lava flows is also a general indicator of proximity to the volcanic vent.

We have undertaken detailed mapping (1:120 scale to 1:5000 scale) of the physical characteristics of the extremely well-preserved, relatively undeformed pillow lavas at the Five Mile Lake prospect. We have measured various features of these pillows, including pillow shape, pillow horizontal dimensions, pillow vertical dimensions, pillow vesicularity, pillow selvedge characteristics, and the thicknesses of chlorite-rich, formerly glassy pillow margins. The relatively high vesicularity of these

pillows (commonly between 10% and 15%), as well as the local presence of multiple pillow selvages suggests that these flows were formed in a relatively shallow (<1 km) subaqueous environment.

Our detailed mapping has also allowed us to identify several shallow mafic dikes that can be seen undergoing a vertical, then lateral transformation into pillow lavas. These regions represent the volcanic vent sites from which these pillow lavas issued. In several vent-proximal locations, chert-rich exhalite horizons (up to 1 meter thick) containing traces to several percent pyrite, sphalerite, and chalcopyrite are also present. Thus, our results support the relationships between proximal volcanic environments and mineralization in lava flow dominated sequences indicated by Gibson et al. (1999).

Of particular interest are the results of our measurements of the thickness of the formerly glassy margins surrounding the pillows at the prospect. We have found that the formerly glassy pillow margins are clearly thicker (>4.5 cm thick) at these vent proximal locations than they are at locations that appear to be more distal to volcanic vents (where they are generally 2cm or less in thickness).

Our results suggest that in pillow-dominated sequences, the thickness of the glassy margin surrounding pillow margins may be an accurate indicator of proximity to volcanic vents. This has significant implications for mineral exploration, as this measurement can be easily and quickly completed during field mapping, and may provide an effective means to identify regions within monotonous pillow sequences that are more likely to contain VMS mineralization.

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A NEW LOOK AT THE 1.1 GA CHENGWATANA VOLCANICS IN THE ST. CROIX HORST, MINNESOTA AND WISCONSIN

Nicholson, S.W., U.S. Geological Survey, MS 954, Reston, VA 20192; Boerboom, T., Minnesota Geological Survey, St. Paul, MN 55114; Cannon, W.F., U.S. Geological Survey, MS 954, Reston, VA 20192; Wirth, K., Macalester College, St. Paul, MN 55105; and Isachsen, C.E., University of Arizona, Tucson, AZ 85721

The 1.1 Ga Midcontinent rift system (MRS) hosts several classes of hydrothermal and magmatic mineral deposits (Nicholson et al., 1992). Recent speculation about the presence of additional magmatic mineral deposits (e.g., "Voisey's Bay"-type Ni-Cu; Schulz et al., 1998) has focused attention on the chemical compositions of rift-related basalts and the identification of central volcanic complexes as exploration tools. The St. Croix horst contains the most southerly exposure of volcanic and sedimentary rocks related to the MRS, but until now, sufficient chemical, age, and geophysical data have not been available to characterize adequately the nature of the volcanic rocks (Nicholson et al., 1997) and their relationship to the regional chemical stratigraphy established for the MRS.

North of the St. Croix horst rift-related rocks are exposed around the margins of Lake Superior and detailed stratigraphic sections are well established. Outcrops within the St. Croix horst are sparse: the volcanic rocks are nearly all subaerial basalt flows and were previously assigned to the Chengwatana Volcanics. Recently Cannon et al. (2001) used new detailed aeromagnetic imaging and age determinations to subdivide the former Chengwatana Volcanics into three units, the Minong Volcanics, the Clam Falls Volcanics, and a newly redefined Chengwatana Volcanics (Fig. 1). More than 200 chemical analyses are now available for volcanic rocks in the St. Croix horst. When compared to the regional chemical stratigraphy recognized previously around western Lake Superior (Nicholson et al., 1997), the three new volcanic units appear to be related as follows.

The youngest unit, the Minong Volcanics, is most similar to the Portage Lake Volcanics (1096-1094 Ma). Both are dominated by low- TiO_2 (less than about 2.0 wt. % TiO_2) basalts with low abundances of incompatible trace elements. Like the Portage Lake Volcanics, the Minong Volcanics contain few rhyolites, but a rhyolite flow near the base of the section has been dated at about 1094 Ma (Lake Nelson rhyolite; Zartman et al., 1997), an age comparable to the upper Portage Lake Volcanics. Basalts with depleted compositions similar to N-MORB occur as flows near the top of the Minong Volcanics and as dikes in the upper Portage Lake Volcanics.

The Clam Falls Volcanics unconformably underlie the Minong Volcanics. It is also dominantly low- TiO_2 basalts, but high- TiO_2 basalts (more than about 2.5 wt % TiO_2 ; increased abundances of incompatible trace elements) are more common in this unit than in the overlying unit. The high- TiO_2 basalts are similar in composition to high- TiO_2 basalts in the Portage Lake Volcanics and the underlying upper Kallander Creek Volcanics (dated at 1098 Ma) to the northeast. Although chemically similar, the metamorphic grade of the Clam Falls Volcanics is considerably higher than the Minong, Portage Lake, or Kallander Creek Volcanics, suggesting that this unit represents exhumation of a more deeply buried portion of the rift (Wirth et al., 1997). A rhyolite flow at the base of the Clam Falls Volcanics yields ages between 1100 and 1102 Ma (unpub. data: K.R. Wirth).

The oldest unit, the newly redefined Chengwatana Volcanics now confined to the volcanic rocks between the Pine and Douglas faults, is dominated by high- TiO_2 basalts with accompanying intermediate and felsic volcanic rocks. This association of high- TiO_2 basalts with intermediate and felsic volcanic rocks has been postulated elsewhere in the rift to be related to central volcanic complexes, sites of prolonged shallow magma chamber development and accompanying volcanism. The Amnicon gabbroic and granophyric intrusive complex southeast of Duluth cuts the base of the redefined Chengwatana Volcanics and most likely represents the magma chamber for a central volcanic complex. The extensive granophyre in the Amnicon pluton is identical chemically to an overlying rhyolite flow. This rhyolite flow has a preliminary date of about 1106 Ma (unpub. data: C.E. Isachsen). Southwest of the Amnicon pluton the Chengwatana Volcanics include more low- TiO_2 basalts as the influence of the localized Amnicon magmatic system diminishes.

In conclusion, the high- TiO_2 basalts and related intermediate and felsic rocks of the redefined Chengwatana Volcanics in the St. Croix horst were probably erupted from localized magmatic sources from about 1107 to about 1102 Ma. This was followed by outpourings of voluminous low- TiO_2 flood basalts characteristic of the main stage of rifting of the MRS after about 1102 Ma, now represented in the St. Croix

horst by the Clam Falls and Minong Volcanics. Central volcanic complexes in the St. Croix horst, such as the Amnicon complex, may be potential exploration targets for Cu-Ni sulfide mineralization, if further study can show the availability of a source of sufficient sulfur to produce segregation of Cu-Ni+PGE metals.

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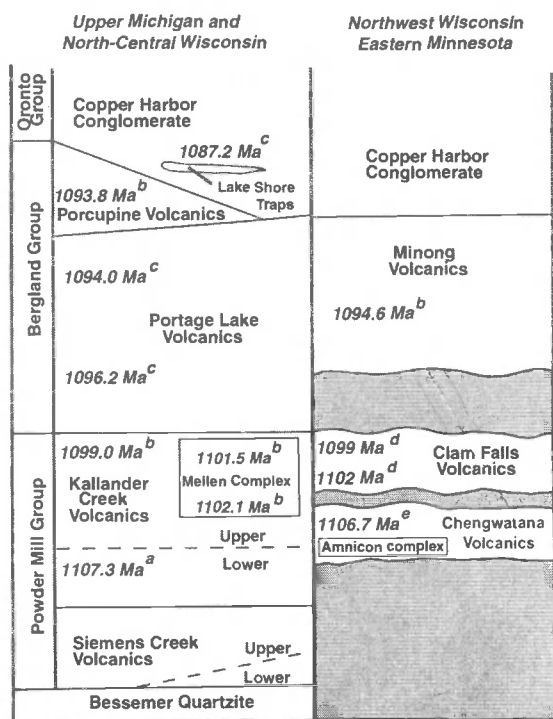


Fig.1 : Stratigraphic column for Keweenaw volcanic rocks on the south shore of western Lake Superior. The U-Pb age dates are from the following sources: a, Davis and Green, 1997; b, Zartman et al., 1977; c, Davis and Paces, 1990; d, unpublished data, K.R. Wirth; e, unpublished data, C.E. Isachsen

OVERVIEW OF ARSENIC OCCURRENCES AND PROCESSES CONTROLLING ARSENIC MOBILITY IN GROUND WATER

D. Kirk Nordstrom
U.S. Geological Survey
Boulder, CO

Introduction

Arsenic concentrations in ground waters can range from less than a few $\mu\text{g/L}$ to tens or even hundreds of mg/L in locally contaminated environments. Both anthropogenic and natural sources for arsenic in ground waters occur in many locations world-wide. Natural sources are causing or have caused poisoning of populations in India, Bangladesh, Chile, Argentina, Mexico, Taiwan, Mongolia, Japan, and China. Mining activities are responsible for arsenic poisoning in Thailand. Arsenic mass poisoning in Bangladesh is the largest known, affecting nearly 30 million people. The processes that enrich arsenic in minerals and in ground waters are complex but apprehensible.

Sources

The geochemical cycle of arsenic from magmatic-hydrothermal processes through weathering, sedimentation, and diagenesis transforms the element in a number of ways that produces an array of present-day natural sources. Probably the single most abundant mineral source of arsenic is arsenian pyrite. Pyrite is ubiquitous in the earth's crust, occurring in sedimentary, metamorphic, and igneous rocks. Arsenic has a strong affinity for the sulfur site in pyrite, substituting up to about 10 wt. % regardless of whether the origin is sedimentary or hydrothermal (Kolkar, Nordstrom, and Goldhaber, 2001). Arsenopyrite contains higher concentrations of arsenic (39-53%) but it is a much rarer mineral. Arsenopyrite and arsenian pyrite are commonly found in association with gold mineralization so that gold mining frequently releases arsenic to the environment. Other arsenic-rich minerals include orpiment, realgar, and enargite. Weathering of these minerals in oxidizing environments solubilizes arsenic as As(III) and ultimately as As(V). Arsenate, or As(V), has a strong adsorption affinity for hydrated iron oxides (Pierce and Moore, 1982) and in oxidized sediments iron oxides can be a source of soluble arsenic if they undergo reductive dissolution during early diagenesis. Geothermal springs are commonly enriched in arsenic, containing 0.1-5 mg/L dissolved arsenic (as both As(III) and As(V)). Geothermal power plants often have to deal with proper disposal of arsenic-enriched waste waters.

Anthropogenic sources of arsenic are numerous. The primary source of industrial and commercial arsenic was arsenic trioxide that was produced as a by-product of metal mining and processing, primarily from copper smelting. More than 300,000 tons of flue dust containing an average of 6.5% arsenic were piled at Anaconda, Montana before removal and disposal. Stockpiles of arsenic trioxide still exist without proper containment and are releasing soluble arsenic to ground waters. Several arsenic insecticides (copper, lead, calcium, magnesium, zinc, and sodium arsenites and arsenates), herbicides (sodium arsenite and methanearsonate, disodium methanearsonate, and cacodylic acid), dessicants (arsenic acid), wood preservatives, animal feed additives, drugs, chemical weapons, and alloys were produced for many years. Roxarsone, an organic arsenical, is still widely used today to

clean parasites out from the stomachs of pigs and poultry (Garbarino et al., 2001).

Transformations and Processes

Arsenic in surface and ground waters occur dominantly as either arsenite, As(III), or arsenate, As(V). Reduction of arsenic occurs with the possible formation of several methylated species, the most prevalent being monomethyl- and dimethylarsenic acid. Several microorganisms including species of fungi, algae, and bacteria catalyze the reduction of arsenic. Methylated arsenic is volatile and is released to the atmosphere in open systems. Oxidation of arsenic is also catalyzed by microbes and it has been demonstrated that soluble As(III) and arsenic sulfide minerals such as arsenopyrite and orpiment can be catalytically oxidized to soluble As(V). More than 25 species of arsenic-oxidizing bacteria have been identified and many more are believed to exist. In geothermal waters, the dominant form of dissolved arsenic is As(III) at the source of the discharge but this can be oxidized rapidly to As(V) by microbes that survive at temperatures of 50-95°C. Little is known about the breakdown of feed additives such as roxarsone. Although there has been research on the transformations of arsenic within humans and some other organisms, the pathways are very complicated and much remains to be learned.

Water quality environments that encourage solubilization and mobility of arsenic are high pH and oxic conditions, anoxic or moderately reducing conditions with no sulfate reduction, anoxic with strongly reducing conditions with little to no sulfate present, or strongly acidic oxidizing conditions (below the normal solubility of hydrated iron oxides). Environments that encourage low arsenic mobility are moderately acidic to neutral and oxidizing conditions, or organic rich sulfate-reducing environments.

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PRELIMINARY EVALUATION OF HYDROTHERMAL ALTERATION MINERAL ASSEMBLAGES AND THEIR RELATIONSHIP TO VMS-STYLE MINERALIZATION IN THE FIVE MILE LAKE AREA OF THE ARCHEAN VERMILION GREENSTONE BELT, NORTHEASTERN MINNESOTA

JASON D. ODETTE, GEORGE J. HUDAK, THOMAS SUSZEK
Department of Geology, University of Wisconsin Oshkosh, Oshkosh, WI 54901

STEVEN A. HAUCK
Natural Resources Research Institute, University of Minnesota -- Duluth, Duluth, MN 55811

The Minerals Coordinating Committee (MCC, State of Minnesota) recently awarded a two year grant to geologists from the Natural Resources Research Institute (NRRI), University of Minnesota – Duluth (UMD), and the University of Wisconsin Oshkosh to further characterize the geology, volcanology and metamorphosed hydrothermal alteration mineral assemblages associated with several volcanic-associated massive sulfide (VMS) prospects in the Vermilion District of northeastern Minnesota. This investigation includes detailed outcrop mapping, diamond drill core relogging, petrography, lithogeochemistry, and geophysical rock property evaluations.

The Five Mile Lake prospect occurs approximately 15 miles southwest of Ely, Minnesota, and is situated within greenschist facies metamorphosed, primarily mafic Archean metavolcanic and metasedimentary rocks within the Lower Member of the Ely Greenstone Sequence of the Vermilion District. In 1994, Teck Exploration Ltd. intersected volcanic-associated massive sulfide (VMS) – style stringer Zn-Cu mineralization in three of four diamond drill holes completed at this prospect. Subsequent studies by the Minnesota Department of Natural Resources (Hudak and Morton, 1999) have suggested that mineralization at Five Mile Lake may be representative of that associated with “Noranda-type” (Morton and Franklin, 1987) Archean VMS

We are currently completing a detailed investigation of the mineralogical, chemical, and spatial characteristics of the metamorphosed synvolcanic hydrothermal alteration that occurs at the Five Mile Lake VMS prospect. Our two-month long field program was completed during the summer, 2000, and consisted of two investigative phases. The first phase comprised GPS-assisted geological mapping of the entire prospect at 1:5000 scale, with more detailed mapping of surface-mineralized zones at 1:120 scale. During our mapping, special attention was paid to alteration mineral assemblages present, and their apparent relationships to locally extremely well-preserved volcanic and volcanoclastic textures. Hand samples were collected from each outcrop. When appropriate, a portable, hand-held diamond drill was used to collect samples of adjacent alteration mineral assemblages. During the second phase of our investigation, Teck Exploration Ltd.’s four diamond drill holes (SXL-1, SXL-2, SXL-3 and SXL-4) were relogged, with particular emphasis being paid to the alteration mineral assemblages and textures present.

Laboratory investigations are currently being conducted. All outcrop and drill core samples have been slabbed and investigated using a binocular microscope for alteration mineral assemblages, alteration textures, and alteration paragenesis. Preparation of one hundred ninety-seven thin sections is currently being completed, and petrographic analyses on the available thin sections are being performed. Fifty-three samples have been analyzed for major and trace elements by ALS Chemex Labs, Inc. (Sparks, NV).

At the present time, we have concentrated our alteration studies on the mafic pillow lava flows and the diabase dikes that occur at the prospect. Based on our preliminary field and laboratory investigations, all pillow lavas at the prospect have undergone varying degrees of hydrothermal alteration. This is consistent with the findings of Peterson (personal communication, 2001), who indicates that the prospect resides within a semiconformable alteration zone comprising at least 30km² of rocks. Three distinct hydrothermal alteration mineral assemblages occur within the pillow lavas at the prospect. The

least altered assemblage (LA) comprises pillow lavas containing a mineral assemblage composed of albite + epidote + chlorite in proportions which are consistent with greenschist facies metamorphism of an original basalt or basaltic andesite lava composition. A quartz + albite + epidote $\pm$ actinolite assemblage (QAE) occurs within pillow cores, whereas a chlorite + actinolite $\pm$ epidote assemblage (CA) occurs in pillow selvages and within the matrix to pillow breccia and pillow hyaloclastite. Locally, CA assemblage filled amygdulites occur within the QAE assemblage pillow cores, and these rocks seem to have a close spatial relationship to thin (<1m thick) mineralized exhalite horizons at the prospect. Textural relationships indicate that the paragenesis of these alteration mineral assemblages is early QAE followed by later CA.

Mass balance analysis of least altered pillow lavas, QAE assemblage, and CA assemblage rocks have been performed using constant Al_2O_3 and best fit (based on Al_2O_3 , TiO_2 , Zr, Nb) isocons (Grant, 1986). Relative to least altered rocks, QAE assemblage rocks illustrate gains in SiO_2 and Na_2O and decreases in CaO, Fe_2O_3 , FeO, MgO, MnO, K_2O , H_2O , Cu and Zn. These trends may be indicative of regional silicification and spilitization from rapidly heated, downwelling, silica-saturated hydrothermal fluid. Relative to least altered rocks, CA assemblage pillows are enriched in MgO, Fe_2O_3 , FeO, Zn and H_2O and are depleted in SiO_2 , K_2O , and CaO. These results may represent an alteration assemblage formed from the mixing of cooler, downwelling Mg-rich seawater and hotter, upwelling Fe- and Zn-rich evolved hydrothermal solutions within permeable pillow selvages and hyaloclastite.

Locally, diabase dikes are altered to epidosite. The epidosite zones comprise rounded to oval, 0.1-1.5 meter diameter patches composed of pale green epidote (locally up to 40%) + quartz $\pm$ actinolite. Preliminary x-ray diffraction analyses indicate that the major epidote mineral in these epidosite zones is clinozoisite. Least altered diabase is composed of a mineral assemblage containing quartz-clinocllore-ferroactinolite and albite with only minor (<5%) epidote and clinozoisite being present. Mass balance analysis of the least altered diabase and the epidosite alteration patches have also been performed using constant Al_2O_3 and best fit isocons. These analyses indicate that the epidosite zones are enriched in CaO, and simultaneously depleted in Na_2O , K_2O , MnO, Fe_2O_3 , FeO, S, Zn, and Cu relative to the least altered diabase. We initially interpret these epidosite patches as areas of locally high water:rock ratio alteration within lower semi-conformable alteration zones associated with high temperature base metal leaching.

At the present time we are in the process of further characterizing the alteration mineral assemblages by means of our laboratory studies. Petrographic and x-ray analyses to further characterize the mineralogy and paragenetic sequences of the alteration mineral assemblages is just beginning, and further geochemical classification of the alteration mineral assemblages will be performed. It is believed that in the long term, further characterization of the alteration mineral assemblages at the Five Mile Lake VMS prospect will provide exploration companies with additional data that is needed to conduct efficient and effective mineral exploration programs for VMS deposits in the Vermilion District.

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CORRELATION OF ARCHEAN ASSEMBLAGES ACROSS THE U.S.-CANADIAN BORDER: PHASE I GEOCHRONOLOGY

PETERSON, Dean M. (Natural Resources Research Institute, Duluth, MN, dpeters1@nrri.umn.edu); GALLUP, Christina (University of Minnesota-Duluth, cgallup@d.umn.edu); JIRSA, Mark A. (Minnesota Geological Survey, jirsa.001@umn.edu); and DAVIS, Donald W. (Royal Ontario Museum, Toronto, ON, dond@rom.on.ca)

Past attempts at temporal correlation of Archean stratigraphic assemblages between rocks of the geochronologically well constrained Shebandowan district of Ontario, and the Vermilion district of northeastern Minnesota (Figure 1), have invariably suffered because: 1) at some scale, one greenstone belt looks pretty much like another; 2) rocks of both districts are dissected by faults having poorly known displacements; and 3) little geochronologic data exists for the Minnesota rocks. Nevertheless, detailed analyses reveal that there are significant stratigraphic and lithologic relationships in each assemblage that can be compared and contrasted. Recent U-Pb geochronology is beginning to shed light on similarities and differences between assemblages in the two areas. Here we report the results of two sets of U-Pb dates on zircons from the Vermilion district.

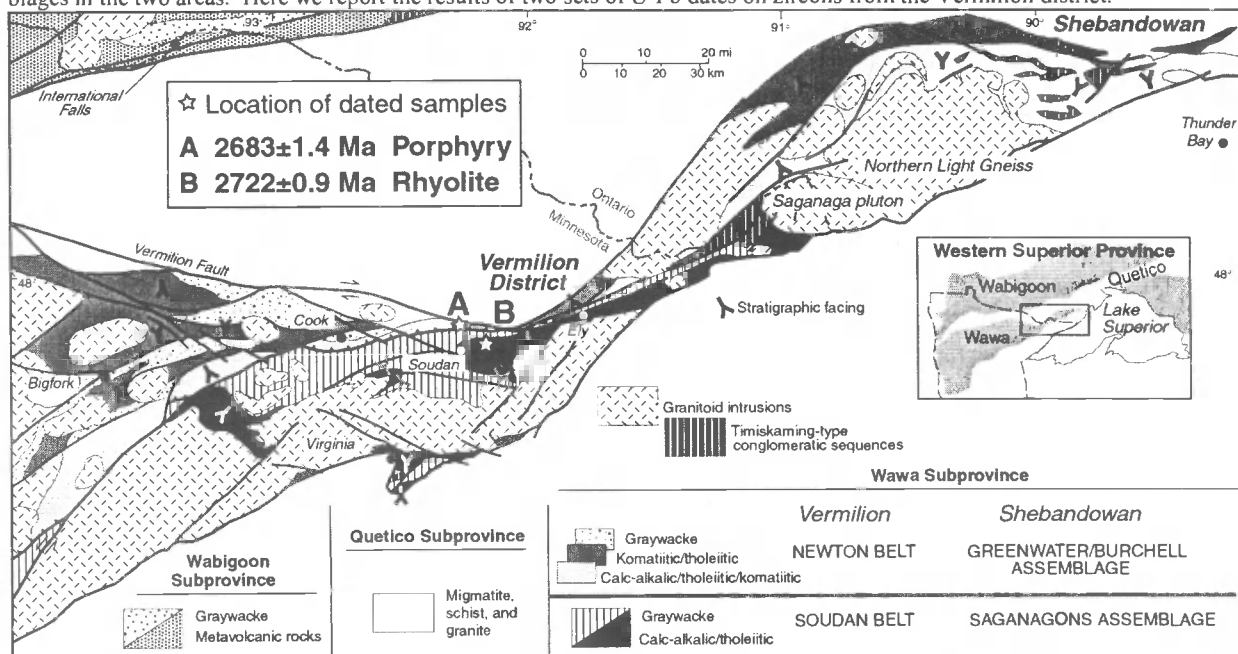


Figure 1. Preliminary correlation of Late Archean stratigraphic assemblages and belts through the Vermilion district, showing the location of dated samples. Inset shows the map location within the western Superior Province.

Rocks of the Vermilion district are subdivided on the basis of stratigraphic and structural contrast into two distinct domains, known as the Soudan and Newton belts (Figure 1). The Soudan belt contains large, broad folds involving calc-alkalic and tholeiitic volcanic strata overlain by, and locally interdigitates with, turbiditic rocks. In contrast, the Newton belt consists of elongate, northeast trending, and mostly northward-younging volcanic and volcanoclastic sequences. Volcanic rocks of the Newton belt differ from those of the Soudan in containing locally abundant komatiitic flows and peridotitic sills (eg. the Newton Lake Formation and Deer Lake sequence). The belts are fault-bounded, and the relationship between stratigraphic units within each belt is largely conformable, though faults obscure contacts locally. In its eastern extension, the Soudan belt is continuous with the Saganagons assemblage that terminates against the Saganaga pluton and Northern Light Gneiss (Figure 1). The Newton belt extends discontinuously eastward into the Shebandowan district, and broadens to form the approximately 2720 Ma-old Greenwater and Burchell assemblages². The Greenwater assemblage is similar to the Newton Lake Formation in younging predominantly to the north, and in containing komatiitic and tholeiitic flows, mafic and ultramafic sills, and local intermediate to felsic flows and pyroclastic rocks. The Burchell is lithologically similar and temporally identical, but youngs to the south. Intrusions in both districts vary from felsic porphyries demonstrably related to volcanism, to large plutons emplaced post-tectonically. Both districts contain unconformable, Timiskaming-type sequences composed of calc-alkalic volcanic rocks, conglomerates, and finer grained sedimentary rocks. These Timiskaming-type rocks include the roughly 2690 Ma-old Shebandowan assemblage² and some lithologic components of the Knife Lake Group in Minnesota⁵.

Periods of generally N-S-directed compression resulted in three major deformation events that are recognized in rocks of both districts. The earliest, D₁, produced broad, locally recumbent folds within the Soudan belt and major fault zones throughout the region. The affect of D₁ on rocks of the Newton belt and much of the Greenwater assemblage appears to have been thrust imbrication of large crustal blocks, resulting in mainly northward stratigraphic facing. Field relationships indicate that uplift, faulting, and the deposition of Timiskaming-type sequences in local fault-bounded basins occurred late in D₁ deformation. The

second deformation event, D_2 , produced synchronous regional metamorphism, foliation development, and structures having largely dextral asymmetry. D_2 has been constrained in the Vermilion district to the time period 2674 Ma to 2685 Ma¹, and between about 2680 and 2685 Ma in the Shebandowan². The abundant NE- and NW-trending faults that dissect the stratigraphic assemblages are assigned to D_3 .

The two samples from the Vermilion district were selected mainly because they had the potential to produce zircons, and their ages would constrain the timing of volcanism and D_2 deformation. Zircons were separated and isotopic compositions were measured at the Royal Ontario Museum in Toronto, using methods developed by Krogh⁴. The samples include: A) **Newton belt** - a weakly deformed, irregularly shaped quartz-feldspar porphyry (QFP) body intruded discordantly along a basalt - iron-formation contact within the Pac Man Pond gold prospect. Field relationships indicate that the QFP was emplaced late in D_2 , because it (and similar intrusions) cuts D_2 shear zones but is itself weakly deformed. B) **Soudan belt** - quartz-phyrlic rhyolite lava flow in the Fivemile Lake VMS prospect. Zircons from the Newton belt sample were very light brown, small (~1 μ g after abrasion), subhedral, prismatic, and typically cracked. The zircons from the Soudan belt sample were colorless to light brown or pink, larger (~2-3 μ g after abrasion), euhedral to subhedral, prismatic, and except for rare grains having a clear core, lacked observable internal cracks. After abrasion, three zircons from each sample were chosen for dating; the results are shown in Figure 2, plotted as 2 sigma error ellipses relative to concordia. Regression and age calculation follow the method of Davis (1982). Only one zircon without cracks could be found in the Newton belt sample. This produced the datum that is closest to concordia (Figure 2). It defines a line with the other data, giving an upper concordia intercept age of 2681 $\pm$ 4 Ma. All data have $^{207}\text{Pb}/^{206}\text{Pb}$ ages that are indistinguishable within error. Under the assumption that Pb loss was recent, the average $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2683.0 $\pm$ 1.4 Ma gives a more precise value for the age of intrusion. The age of this late-syn D_2 porphyry constrains the maximum age of D_2 in the Vermilion district, and is similar in age to parts of the Giants Range batholith, which forms the southern margin of the Vermilion greenstone belt. Data from the Fivemile Lake rhyolite zircons plot very near concordia and have indistinguishable $^{207}\text{Pb}/^{206}\text{Pb}$ ages that average to 2722.6 $\pm$ 0.9 Ma. This is the first age ever reported for the Ely Greenstone, and is similar in age to rhyolites in the Greenwater assemblage in Shebandowan district.

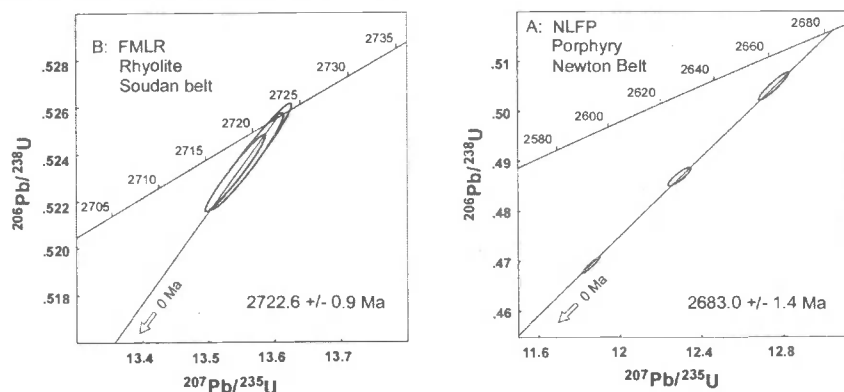


Figure 2. U-Pb isotopic compositions for A) Porphyry in the Newton Belt, and B) Rhyolite in the Soudan Belt.

The ca 2720 Ma volcanic rocks in the Vermilion and Shebandowan districts, as well the Manitouwadge area^{6,7} farther to the east, together with the bracketed ages for D_2 deformation that are nearly identical in all three districts, implies that this terrane defines a major orogen extending more than 600 kilometers. The individual belts have been strongly attenuated by deformation and pluton emplacement, but further U-Pb dates will continue to explore the Vermilion district in this broader orogenic context.

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MAGNETIC SURVEY NEAR WATERLOO WISCONSIN

PEYCHAL^{1*}, C., KEAN¹, W. F., and SCHAPER^{2*}, D., Department of Geosciences,
University of Wisconsin -Milwaukee¹, Department of Geological Engineering,
University of Wisconsin-Madison². wkean@uwm.edu. (* student)

The Waterloo Wisconsin area continues to provide geologic puzzles because of its diverse bedrock. The Waterloo Quartzite is considered by most as coterminous with the Baraboo Quartzite. A mafic dike is known from two quarries about 1 mile apart along a north-south strike, and a coarse feldspar rich pegmatite appears within 200 meters north of the quartzite quarry in which the mafic dike is found (Luther, 1977). The age relationship of these three rock types is still uncertain. Although, the two igneous rock types intrude the quartzite, and both are dated in the range of 1.45 -1.5 Ga. (Van Schmus et al. 1978, Brown, 1986), which is not necessarily the primary age. Paleomagnetic studies on the mafic dike provide a well defined magnetic direction of Dec.=299°, Inc.=43°, N=26, Alpha 95= 13.7°, giving a paleopole at 323°E, 2°S which is interpreted as a 1.7Ga. pole position (Schaper and Kean, 1999).

The object of this study is to better define the magnetic basement in this region in an attempt to clarify the relationship of these known rocks. A proton precession magnetometer survey covered most of the roads in the vicinity of the old Portland Quarry and the Michels Materials Quarry. A first survey covered the region at 0.1 mile spacing. Selected locations were resurveyed at 50 meter spacing, and also with a continuously reading rubidium vapor magnetometer. Finally one road section was covered at 2 meter spacing. Well construction reports, and the aeromagnetic maps of the region were examined for additional insight into the bedrock.

The aeromagnetic maps show a general decreasing trend from west to east, with a 200 nT. anomaly northeast of the Michels Materials quarry, where well construction reports indicate granite. The ground magnetic survey shows a 1000 nT. negative anomaly along Highway 19 that appears to be in line with the known outcrops of the mafic dike. The negative value is consistent with the negative remanent magnetism of the mafic dike. Similar anomalies are found on the south-north section of Hubbleton Rd. which passes in front of the active quarry. We interpret these as the extension of the dike to the north east of its known outcrop.

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Nd and U-Pb Isotope Studies of the Syenitic Aurora Sill, Mesabi Range, Minnesota

Phillips, Erin H., Macalester College, St. Paul, MN 55105; Wirth, Karl R., Geology Department, Macalester College, St. Paul, MN 55105, wirth@macalester.edu; Vervoort, J.D., and Gehrels, G.E., Dept. of Geosciences, University of Arizona, Tucson, Arizona 85721

The Aurora sill is a concordant tabular intrusion approximately 5.6 km long and 6 to 37 meters thick that occurs in the Mesabi Range north of the town of Aurora, Minnesota. The age of the sill is unknown, but it has commonly been assigned a Mesoproterozoic (Keweenawan) age because it intrudes the 1.88 Ga Biwabik Iron-Formation and also because of its resemblance to granitic complexes, or “granophyres”, of the Midcontinent Rift (White, 1954). The geochemistry and petrography of the Aurora sill, however, are quite different from the Midcontinent Rift (MCR) granophyres (Phillips et al., 2000). The isotopic data presented here indicate that the Aurora sill has a Keweenawan age and represents a unique occurrence of this rock type in this portion of the MCR.

Mineralogically, the Aurora sill is composed of albite, potassium-feldspar, aegerine, fibrous amphibole, chlorite, Fe-Ti oxides, Fe sulfide, and zircon and is classified as a syenite (< 5% normative quartz or nepheline) based on both modal and normative compositions. The presence of two feldspars indicates subsolvus crystallization and high P_{1120} . Albite is the predominant mineral in the sill and is aligned in fine-grained samples to produce a trachytic texture. Samples from the Aurora sill exhibit limited geochemical variation ($\text{SiO}_2=54.6\text{-}60.7$ wt. percent; $\text{Mg\#}=0.4\text{-}0.75$; $\text{Y}=9\text{-}19$ ppm) suggesting that the intrusion has undergone relatively minor internal fractionation.

A large sample from the Aurora sill yielded only a few small (60–80 μm) anhedral zircons. No crystal faces were present on any of the zircon grains but it is unknown whether this is due to fracturing during processing or resorption of the grains. Four U-Pb zircon analyses (each consisting of 3 small zircons) yield a highly discordant regression with an upper intercept of 2970 ± 257 (2 σ ; Figure 1). It is improbable that this date represents the age of the sill because it intrudes the Biwabik Iron-Formation that was deposited about 1.88 Ga (Fralick et al., 1998). Our interpretation is that the zircons grew in the Mesoproterozoic with significant inheritance from Archean basement rocks in the region. The lower intercept of 1190 ± 466 Ma indicates either zircon growth or a Pb loss event in the Mesoproterozoic that may have coincided with intrusion of the sill. Nd isotopes provide further evidence of a Keweenawan age for the Aurora sill. A slightly negative epsilon Nd value of -1.4 results when an age of 1,100 Ma is assumed for the Aurora sill (Figure 2). If older ages are used, they result in unrealistically high ϵ_{Nd} values ($\epsilon_{\text{Nd}} = +9$ @ 1,800 Ma; $\epsilon_{\text{Nd}} = +23$ @ 2,900 Ma). The Nd isotopic results corroborate a Keweenawan age (~1.1 Ga) for the sill and are consistent with the lower U-Pb zircon intercept.

If the Aurora sill is Keweenawan in age, the sill would represent a relatively rare type of alkaline magmatism in this part of the MCR. The sill is distinct from the granophyric complexes of the northwestern limb of the MCR in several respects. The granophyric textures and modal quartz that are typical of felsic rocks of the MCR are not present in the Aurora sill. The sill is saturated to weakly undersaturated in silica and contrasts sharply with the silica saturated granophyres of the MCR. Furthermore the Aurora sill is characterized by high total alkalis, Nb/Y, and Ce/Zr compared with felsic rocks of the MCR. The Aurora sill also lacks the negative Nb anomalies that are characteristic of the MCR granophyres. Although there are no known Keweenawan syenites in the vicinity of the Aurora sill, there are several alkaline intrusions in the northern portion of the MCR. The Coldwell Complex and Killala Lake Complex both contain syenites that have been dated at 1108 ± 1 Ma, near the

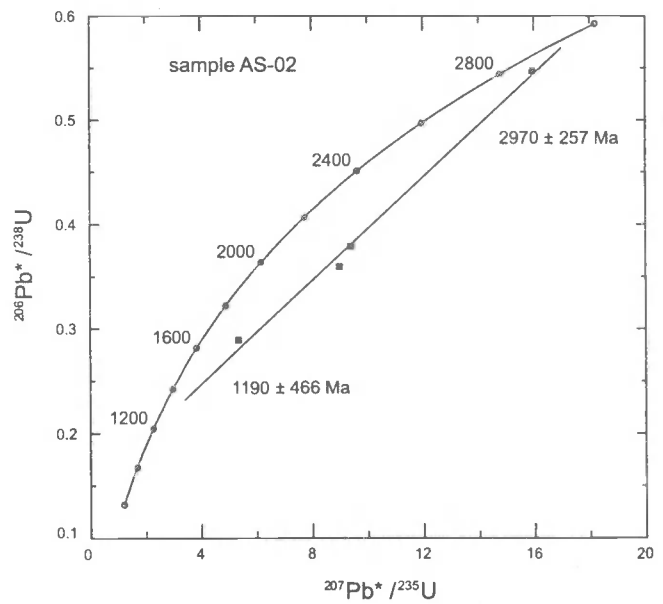


Figure 1

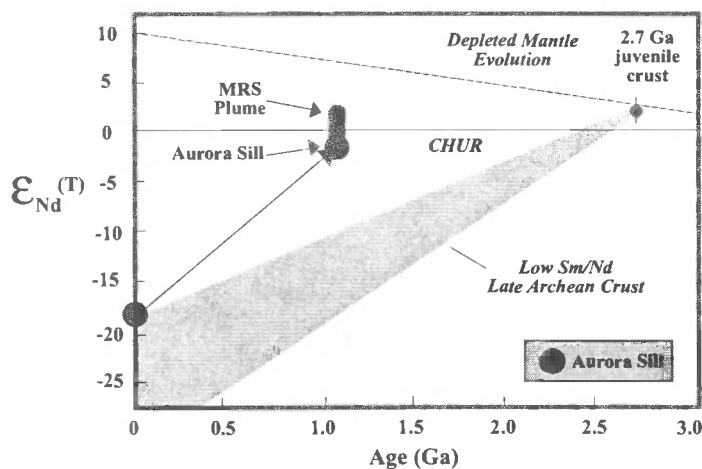


Figure 2

older zircons. It is difficult to imagine a process whereby zircons are inherited from the extant Archean crust without that crust contributing a highly unradiogenic Nd isotopic signature (negative ϵ_{Nd} values) to the sill. This could occur if the assimilant was of low concentration and/or near-chondritic Sm/Nd ratios, but neither is a common characteristic of zircon bearing lithologies. One possibility is that the zircons in the Aurora sill have been derived from small degrees of assimilation of Biwabik Iron-Formation or related Animikie sediments. These sediments have variable but generally less negative ϵ_{Nd} values in the Mesoproterozoic (Hemming et al., 1995) and also contain Archean detrital zircons.

The age of the Aurora 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 (1.6-2.5 Ga). 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. Since a Keweenaw Aurora sill could not have had an effect on ore-formation in the Paleoproterozoic, it is not possible at this time to confirm the model described by Morey (1999).

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beginning of continental rifting (Heaman and Machado, 1992). Preliminary examination of the geochemistry of these syenites displays similarities to the Aurora sill. For example, they exhibit high Nb/Y ratios and follow similar trends on many geochemical plots (e.g., $\text{Na}_2\text{O}+\text{K}_2\text{O}$ versus SiO_2) and have broadly similar ϵ_{Nd} values to the early gabbro phases from the Coldwell complex (Heaman and Machado, 1992). Unlike the Coldwell and Killala Lake complexes, the Aurora sill is not known to be associated with carbonitites.

The Nd isotopic and trace-element signatures of the Aurora sill suggest that it was derived from a mantle melt that did not interact with older, evolved crustal materials. However, this interpretation is not fully consistent with the U-Pb zircon data which clearly indicate inheritance of

Freeze/Thaw Testing of Carbonate Aggregate Sources in Wisconsin – A Status Report

Daniel D. Reid, Wisconsin Department of Transportation, 3502 Kinsman Blvd., Madison, Wisconsin 53704-2507

Delamination and deterioration of exposed pavement aggregates has been a common occurrence on highways in southern and northeastern Wisconsin, and has lead to highway maintenance problems in some areas. The principal cause of these problems is crushed stone aggregate produced from Sinnipee Group (Galena, Decorah and Platteville Formations) rock. Prior to 1999, the Wisconsin Department of Transportation (WisDOT) excluded entire formations and members of the Sinnipee Group as a way of mitigating pavement problems. A study of carbonate aggregate resources in Wisconsin, conducted jointly by WisDOT and the Wisconsin Geologic and Natural History Survey (WGNHS), provided a comprehensive analysis of the stratigraphy and geologic properties of Sinnipee Group aggregate resources. This study identified significant regional variability in Sinnipee Group rock, and concluded that the laboratory freeze/thaw test was the most effective method of identifying problem aggregate sources. Based on this data, WisDOT concluded that specifications excluding certain formations and members were not appropriate for uniform application across the entire state.

As a result of the WisDOT/WGNHS carbonate aggregate study, WisDOT developed and implemented specifications for freeze/thaw testing of carbonate aggregate sources used in pavements and bridge decks in October 1999. These specifications mandated freeze/thaw testing in counties where Sinnipee Group rock outcrops, and set the threshold for loss at 18% by weight. Included in the specifications was a clause that allows WisDOT to waive freeze/thaw testing for existing aggregate sources determined to be in the Silurian System or Prairie du Chien Group of carbonate rocks. WisDOT has now completed over 230 independent freeze/thaw tests on carbonate aggregate source material throughout Wisconsin. To date, the results indicate that freeze/thaw testing is performing it's intended function. A decrease in pavement problems has been reported and WisDOT now has an effective method of controlling aggregates that produce excessive delamination. As an added benefit, aggregate producers are now permitted to use aggregate sources that were excluded prior to establishment of the freeze/thaw testing specification, so long as material from these sources tests under the 18% threshold.

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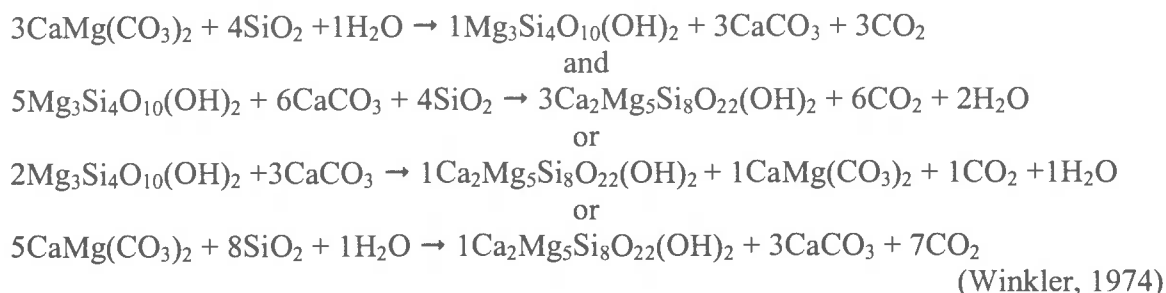
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A Metamorphosed Evaporite Sequence from the Sibley Basin

Rogala, B. and Fralick, P.W., Department of Geology, Lakehead University, Thunder Bay, Ontario

The Sibley Group sediments were deposited in a subsiding intracratonic basin (Fralick and Kissin, 1995), between 1339 ± 33 Ma (Franklin *et al.*, 1980) and 1537 ± 10 -2 (Davis and Sutcliffe, 1984). The Group is divided into three main Formations: Pass Lake, Rosspport, and Kama Hill, representing deposition in a braided fluvial-mudflat-playa environment (Cheadle, 1986). This study concentrates on a section through a lateral correlative of the cyclic facies contained in the Rosspport Formation present in the Noranda drill core NI-92-5. The location of this drill hole is north of other cored sections and outcrops of the cyclic facies and represents a more basin center environment. The cyclic facies to the south consists of alternating layers of dolomite and red shale with individual layers, in the approximately 40 m thick assemblage, varying from mm- to dm-scale. In drill hole NI-92-5 the layering is at a similar scale, but is composed of alternations between what was first thought to be dolomite-rich and gypsum-rich intervals, reflecting wet and dry seasonality in the central playa environment.

SEM and XRD analysis indicate that the sequence was metamorphosed. The progression of metamorphic facies, from lower to higher T towards the diabase sill, is represented by the following reactions:



Near the diabase sill pargasite, a hornblende with the composition $(\text{Na},\text{K})_{0-1}\text{Ca}_2\text{Mg}_4\text{Al}_3\text{Si}_6\text{O}_{22}(\text{OH})$, is the dominant mineral. Clinocllore, a chlorite mineral with a composition of $\text{Mg}_5\text{Al}_5\text{Si}_3\text{O}_{10}(\text{OH})$, is found throughout the metamorphic series. Both of these minerals are common in magnesian carbonate metamorphism (Pattison and Tracy, 1991).

Primary layering has been masked in places by metamorphism. However, S.E.M. analysis clearly shows the mineralogical layering, reflecting variations in primary geochemical constituents between individual laminae. ICP-AES analysis also highlights the varying compositions of the sequence. Ca/Mg ratios indicate the precipitation of gypsum in many layers. This is supported by the observation of gypsum using S.E.M.. The pargasite tends to exist in layers with differing K and Na proportions. The K^+ and Na^+ ions may reflect the incorporation of KCl and NaCl. Both of the minerals are found in S.E.M. sections taken near the middle of the sequence.

Clastic input is variable between individual layers, but shows an increase at the top of the section. This increase is related to the appearance of sand sheets, which typically mark the end of the cyclic facies in the Sibley Group sediments. Clastic material becomes slightly enriched in elements denoting a mafic rock source up-section.

The source material is distinctly alkalic. Alkalic material may be associated with plume activity, which would fit the intracratonic theory for the formation of the Sibley Basin. However, suitably alkalic rocks have not been found in the area.

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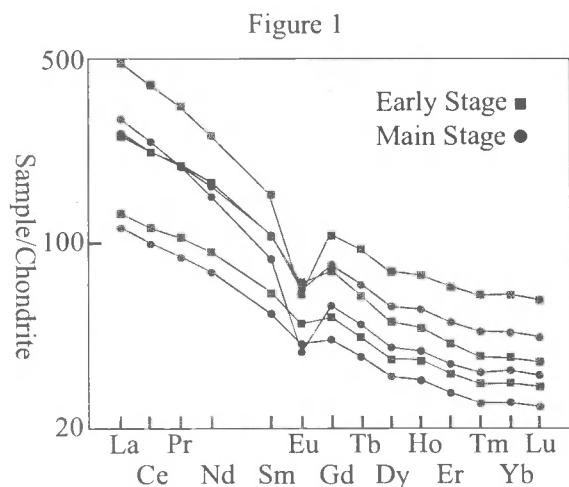
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Roles of Fractional Crystallization and Assimilation in the Production of Midcontinent Rift Granophyres.

Sandland, Travis O., (tsandland@Macalester.edu) & Wirth, Karl R., Geology Department, Macalester College, St. Paul, MN, 55105; Vervoort, Jeff D. & Gehrels, George E., Department of Geosciences, University of Arizona, Tucson, AZ, 85721; Kennedy, Bryan C., Geology Department, Macalester College, St. Paul, MN, 55105; Harpp, Karen S., Department of Geology, Colgate University, Hamilton, NY, 13346

The granitic complexes of the Midcontinent Rift (MCR), commonly termed granophyres, comprise a significant portion of the Duluth Complex in northern Minnesota. They range in size from 30 to 150 km² in surface area and are 1 to 2 km in thickness. They consist of basal diorite and monzodiorite and progress upward to quartz monzodiorite, granodiorite, and granite. This study focuses on the petrogenesis of four of these complexes: the Greenwood Lake, Misquah Hills, Eagle Mountain, and Pine Mountain granophyres.

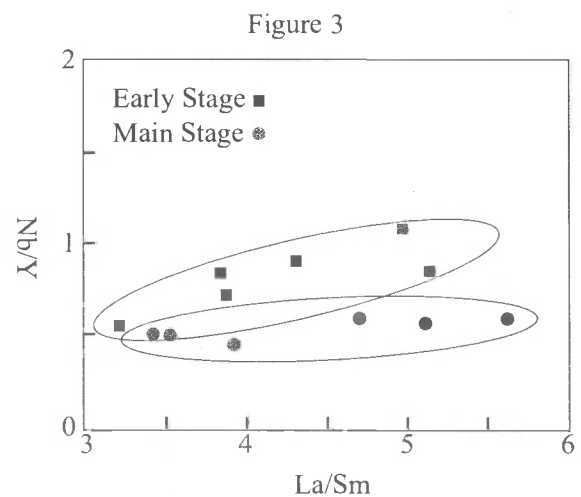
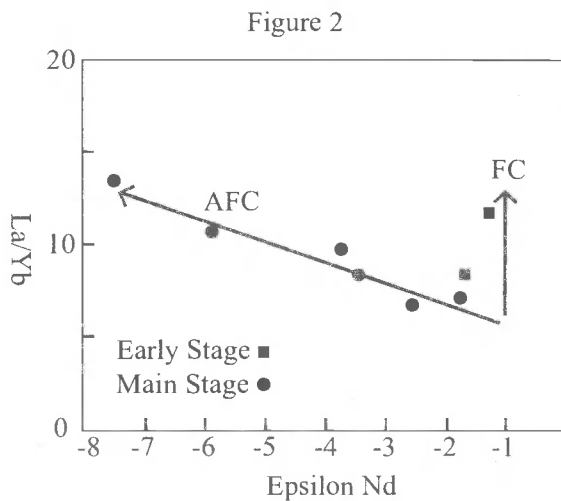
Miller and Vervoort (1996) identified two magmatic stages in this part of the MCR. An "early stage" from 1108-1105 Ma, and a "main stage" from 1100-1094 Ma. The four granophyre complexes addressed in this study have U-Pb zircon ages consonant with this chronology. The older granophyres include the Misquah Hills and Greenwood Lake complexes with ages of 1106±6 Ma and 1106±3 Ma (±2 sigma), respectively, and were emplaced during the early stage of the rift. The Eagle Mountain and Pine Mountain granophyres have ages of 1098±4 and 1095±4 Ma, respectively, and were emplaced during the main magmatic stage.



The granophyre complexes vary widely in composition (47-76 wt. % SiO₂) and plot as linear trends on many Harker variation diagrams. The two granophyre groups (early and main stage) are indistinguishable on such plots and appear to have very similar major element chemistry. Incompatible trace elements (including REEs) are enriched in both groups (Fig. 1) although the early stage granophyres generally have higher concentrations than the late stage granophyres. Incompatible trace element ratios (e.g., La/Sm, Gd/Yb) are similar for both groups. The early stage granophyres have initial epsilon Nd values between 0 and -2. In contrast, the main stage granophyres are isotopically enriched, with initial epsilon Nd values between -3 and -8.

The isotopic and incompatible element data suggest both fractional crystallization (FC) and assimilation fractional crystallization (AFC) processes were involved in the evolution of the granophyres. The large negative epsilon Nd values associated with the main stage granophyres indicate AFC processes and suggest contamination by an isotopically enriched source, possibly felsic Archean crustal rocks. This trend can be seen on a graph of epsilon Nd vs. La/Yb (Fig. 2). The main stage granophyres also

have low Nb/Y ratios, a signature of contamination by crustal materials, whereas the Nb/Y ratios of the early stage granophyres are positively correlated with La/Sm (Fig. 3). If AFC processes were active during the formation of the early stage granophyres, the assimilant was likely limited to juvenile mafic rocks with little or no isotopic enrichment. Alternatively, the enrichment of incompatible elements in the early stage granophyres could be the result of fractional crystallization.



These data support the model of rift evolution as presented by Vervoort and Green (1997). The early stage granophyres were formed either by fractional crystallization, or by AFC processes with contamination from a high Sm/Nd mafic crust. During this stage of rift evolution, the middle to upper crust was probably relatively cold, so assimilation likely occurred in the lower crust due to local heating as a result of plume initiation. The main stage granophyres are isotopically contaminated and suggest AFC processes at work. During this time period, renewed rifting resulted in higher ambient temperatures in the crust, and allowed melting of older, low Sm/Nd, negative epsilon Nd sources, possibly at middle to upper crustal levels.

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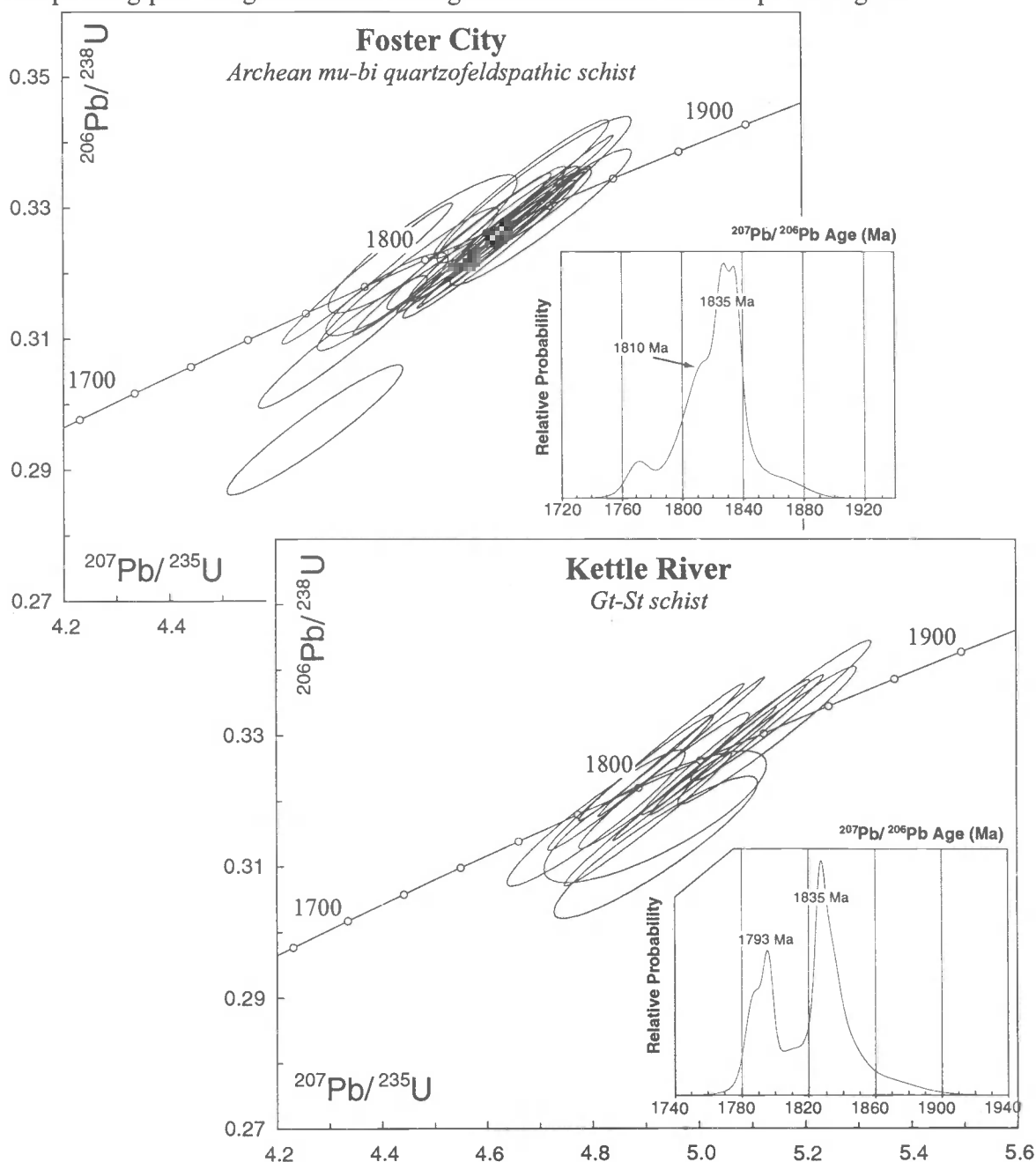
DIRECT TIMING CONSTRAINTS ON PALEOPROTEROZOIC METAMORPHISM, SOUTHERN LAKE SUPERIOR REGION: RESULTS FROM SHRIMP U-PB DATING OF METAMORPHIC MONAZITES

Schneider, D.A., Syracuse University, Syracuse, NY, 13244; **Holm, D.K.**, Kent State University, Kent, OH, 44242; **Hamilton, M.A.**, Geological Survey of Canada, Ottawa, ONT, K1A 0E8

The age of the Penokean Orogeny has been firmly established for decades by U-Pb pluton age data. The timing of post-orogenic cooling and lower temperature overprinting has only been established more recently by thermochronologic investigations. Little information exists however on the timing of the initial higher-grade metamorphism which affected the southern Lake Superior region during the Paleoproterozoic. Such information represents a critical missing link in our understanding of the tectonothermal evolution of the crust during and after Penokean orogenesis. Monazite, a REE-phosphate accessory mineral, grows as a common metamorphic phase under amphibolite and higher-grade conditions. Monazite U-Pb ages typically yield reliable estimates for the timing of peak metamorphism, although post-metamorphic deformation and fluid flux can cause lower-temperature monazite dissolution and reprecipitation. We utilized the SHRIMP at the GSC in Ottawa to obtain geochronologic information on distinct mineral domains (e.g., core vs. rim) which may have resulted from particular tectonothermal events. Through BSE imaging prior to analyses, we found rim textures spatially distinct from interior replacement textures. Age data are indistinguishable from each domain and replacement probably resulted from the same thermal event as the rim neogrowth. Age data summarized below include only concordant or near concordant analyses and are reported as weighted average $^{207}\text{Pb}/^{206}\text{Pb}$ ages.

In this pilot study we separated monazite from an amphibolite grade Paleoproterozoic metasedimentary unit in east-central Minnesota (Kettle River locality) and from an Archean gneiss unit within the Peavy district, northern Michigan (Foster City locality). From Kettle River, a sample of garnet schist, which attained peak metamorphic conditions of 470-520°C at 5-6 kbar, yielded distinct populations of core and rim U-Pb ages from 5 monazite grains. Eight analyses of core domains yielded a U-Pb monazite crystallization age of 1834.0 ± 6.1 Ma, reflecting primary metamorphic growth. A population of monazite rim/replacement spot analyses, characterized by a higher Th content, yielded an age of 1792.9 ± 4.3 Ma. This latter age is similar to the ~1799 Ma U-Pb crystallization age of the deformed Hillman tonalite (Van Schmus et al., 2000, ILSG and this volume). From Foster city (>500°C and ~4 kbar), an Archean muscovite-biotite quartzofeldspathic gneiss yielded a monazite core age of 1834.4 ± 6.0 Ma from 10 spots on 11 grains. Rim/replacement domain analyses from 9 spots yielded a younger age of 1809.8 ± 6.3 Ma, consistent with high-temperature cooling in the region (1800 and 1785 Ma Ar-Ar hornblende ages; Mancuso et al., ILSG, 1997).

These metamorphic U-Pb ages are the first reliable metamorphic dates from this Paleoproterozoic orogen and indicate a widespread thermal pulse at 1835 Ma in response to accretion-induced crustal thickening. Albeit preliminary, the age of metamorphism is remarkably consistent across the orogen. High temperature Ar-Ar cooling ages on hornblende (~500°C) from north of the Watersmeet dome (~1822 Ma; Schneider et al., 1996, CJES) and biotite Ar-Ar dates from low-grade structural panels from east-central Minnesota (1840-1830 Ma; Schweitzer et al., 2000, ILSG) are compatible with an ~1835 Ma orogenwide metamorphic episode. Further accessory mineral geochronology holds promise for better elucidating the timing of syn-orogenic metamorphism, as well as overprinting post-orogenic events throughout the southern Lake Superior region.



RESULTS OF IGNEOUS THERMOMETRY AND BAROMETRY ON THE EAST-CENTRAL MINNESOTA BATHOLITH: EVIDENCE FOR POST-EMPLACEMENT EXHUMATION AND COOLING

SCHWEITZER, D., and HOLM, D., both at Dept. of Geology, Kent State University, Kent, OH, 44242; VAN SCHMUS, W.R., Dept. of Geology, Univ. of Kansas, Lawrence, KS, 55045; BOERBOOM, T., Minnesota Geological Survey, 2642 University Avenue, St. Paul, MN

The internal zone of the Penokean orogen in east-central Minnesota was invaded by abundant plutonism associated with emplacement of the East-Central Minnesota Batholith (ECMB) from 1787 to 1772 Ma (Van Schmus et al., 2000). Previous application of the Aluminum-in-Hornblende (AH) igneous barometer on phases of the ECMB indicate paleodepth estimates that increase from ~13 km in the north (Ka-F, K-4; Fig 1) to ~18 km in the southeast near St. Cloud (SC, Fig. 1). Holm and others (1998) inferred the depth differences to reflect intrusion of different magma bodies into a rapidly unroofing terrane. This interpretation predicts that progressively younger intrusions would have been emplaced into progressively shallower crustal levels. At the time, their hypothesis was limited by the lack of any precise age data on the intrusions analyzed. The new ECMB U-Pb age data provides the framework to directly test this hypothesis of syn-emplacement exhumation.

We selected six new samples for further AH barometric work (starred localities, Fig 1). Anderson and Smith (1995) outlined the important role that temperature plays in the Al concentration in hornblende rims and proposed a temperature correcting calibration for the application of the AH barometer. For this reason, the Hornblende-Plagioclase (HB-PL) thermometer (Blundy and Holland, 1992) was applied to these samples in order to derive a crystallization temperature estimate for each sample. The Schmidt (1992) pressure calibration is presented in order to compare the effects of the temperature correction. The electron microprobe at the University of Maine, Orono was used to obtain compositional data used for both the AH barometer and HB-PL thermometer. The results of these analyses are summarized in the following table.

Table 1: Summary of igneous thermometry and barometry results

Sample ID	Rock Unit	An Content (%)	B and H, 1990 Temperature (°C)	Schmidt, 1992 kbar	A and S, 1995 kbar
EC-31	Granodiorite	49.99	789 ± 38	9.1 ± 0.6	<6.5 ± 0.6
EC-15	Mafic Plug	59.35	884 ± 38	13.4 ± 0.6	<6.2 ± 0.6
DS-99-17	Anne Lake Granite	31.29	745 ± 38	6.0 ± 0.6	4.9 ± 0.6
EC-1	Watab Quartz Diorite	40.01	696 ± 38	5.2 ± 0.6	5.0 ± 0.6
EC-35	Granodiorite	43.77	746 ± 38	8.5 ± 0.6	<7.2 ± 0.6
RFG-7	Reformatory Granodiorite	51.31	783 ± 38	6.4 ± 0.6	4.4 ± 0.6

Assuming an average overburden density of 2.7 g/cc, the pressures recorded by EC-31, EC-15, and EC-35 correspond to maximum emplacement depths of 23-27 km. These appear to be anomalously high when compared to other rocks in the area and probably reflect artificial Al enrichment of hornblende crystal rims due to high An content. Samples RFG-7 (17 km), EC-1 (18 km), and DS-99-17 (18 km) when corrected for temperature effects appear to preserve viable estimates since they are consistent with prior barometric results.

In the north, samples Ka-F and K-4 (Fig. 1) both preserve emplacement depths of 13 km but their U-Pb ages are 15 m.y. apart. To the south, all samples near St. Cloud record ~17-18 km depths regardless of age. This implies that very little uplift occurred during emplacement of the ECMB. The bulk of post-tectonic exhumation appears to have occurred *after* the emplacement of the ECMB. Preserved pressure differences probably reflect deeper emplacement depths (from N to S) across the batholith. Post-emplacement exhumation is consistent with cooling ages being 10-20 m.y. younger than crystallization ages from the batholith (Holm et al, 1998; Holm and Lux, 1996). The ECMB was likely completely exhumed prior to deposition of the Early Proterozoic (1750-1650 Ma) red quartzites.

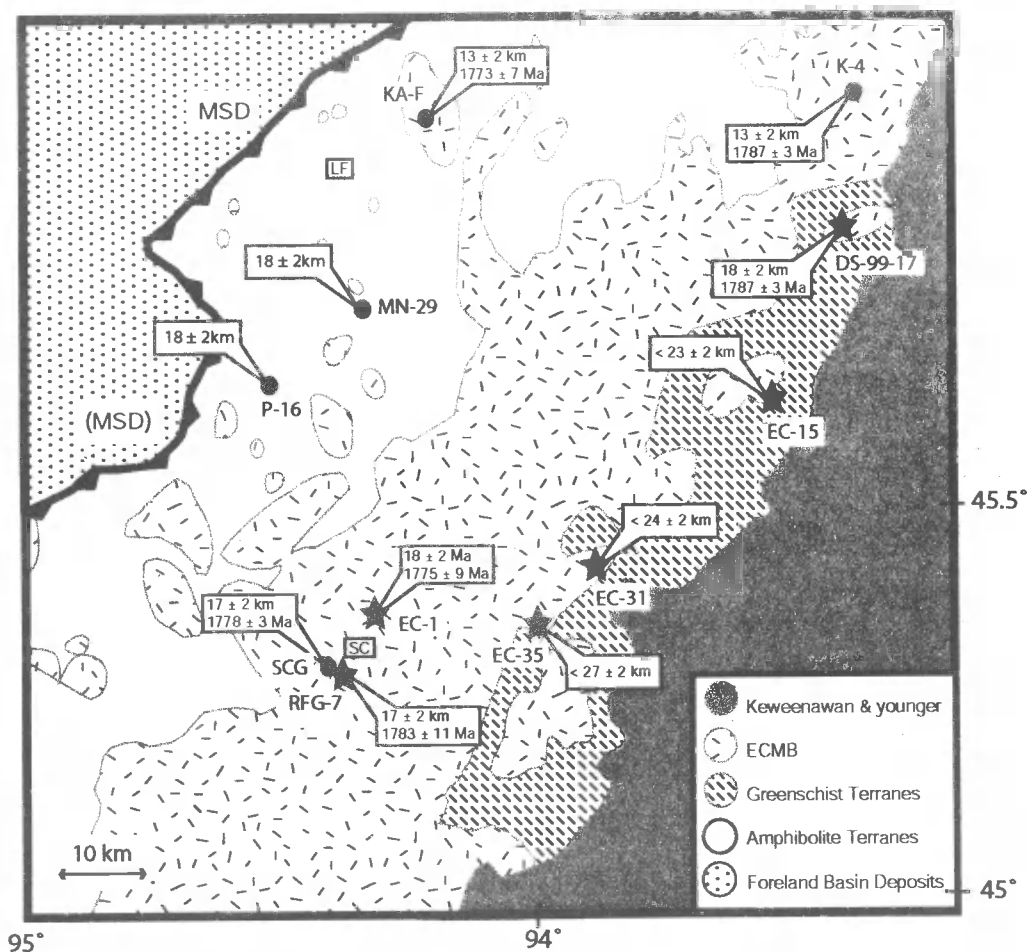


Figure 1: Simplified map of the internal zone of the Pekkonean orogen. Localities marked with filled circles represent samples analyzed by Holm et al (1998). Starred localities denote samples analyzed in this study. MSD = Malmo Structural Discontinuity; SC = St. Cloud; LF = Little Falls. U-Pb ages after Van Schmus et al (2000).

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A SYNOPSIS OF ARCHEAN AND PROTEROZOIC PLATINUM GROUP ELEMENT MINERALIZATION IN THE THUNDER BAY DISTRICT, ONTARIO

SMYK, Mark C., MASON, John K. and SCHNIEDERS, Bernie R., Ontario Geological Survey, Ministry of Northern Development and Mines, Suite B002, 435 James St. South, Thunder Bay, ON P7E 6S7, and STOTT, Greg M., Ontario Geological Survey, Ministry of Northern Development and Mines, Willet Green Miller Centre, 933 Ramsey Lake Road, Sudbury, ON P3E 6B5

Platinum group element (PGE) occurrences and deposits are in both Neoarchean and Mesoproterozoic mafic to ultramafic intrusive rocks in the Thunder Bay District. Recent, dramatic increases in platinum group metal prices have prompted renewed interest in PGE exploration, resulting in the discovery of hitherto unknown hosts and styles of mineralization.

Archean

There are four broad, temporally diverse settings for Neoarchean PGE mineralization:

- (1) Pre-tectonic, mafic to ultramafic, subvolcanic(?) intrusions intimately associated with greenstone belts of various ages in the Wawa and Wabigoon subprovinces;
(e.g. Haines Gabbro (Shebandowan belt / Wawa; 2722 Ma); Core Zone gabbro (Obonga Lake belt / Wabigoon; 2733 Ma);
- (2) Post-tectonic, mafic to ultramafic intrusions (*ca.* 2692 Ma), related to late plutonism in the Wabigoon Subprovince, hosted by gneissic tonalite-granodiorite
(e.g. Lac des Iles and Tib Lake complexes; Buck Lake, Legris Lake, etc.);
- (3) Syn- to post-tectonic, mafic to ultramafic intrusions (*a.k.a.* "Quetico-type"; *ca.* 2680 to 2688 Ma) hosted by Quetico subprovince metasedimentary rocks
(e.g. Samuels Lake, Kawene, Nym Lake, Chief Peter Lake, North Elbow Lake, etc.); and
- (4) Mafic intrusive rocks occurring within syn- to post-tectonic, diorite-monzodiorite-monzonite suites with sanukitoid affinity (*ca.* 2680 to 2685 Ma), within the Wabigoon, Quetico and Wawa subprovinces (*cf.* Stern *et al.* 1989)
(e.g. Roaring River Complex; Entwine Lake).

Disseminated to locally net-textured chalcopyrite, Fe-sulphides, pentlandite and magnetite typically characterize PGE-mineralized zones, which are commonly associated with intrusive contacts, polyphase intrusive breccias, as well as sheared and hydrothermally altered zones.

Proterozoic

Mesoproterozoic intrusive rocks associated with the Midcontinent Rift locally range in age from *ca.* 1108 Ma (e.g. reversely polarized Coldwell alkaline complex; Logan diabase) to ages younger than the magnetic polarity reversal that occurred between 1105 and 1102 Ma (Davis and Green 1997). A tabulated synopsis is provided below:

Intrusion / Lithology	Mineralization Style	Local Examples (Associated PGE-Mineralized Areas)
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Normal Magnetic Polarity
< (1005-1102 Ma):

Layered(?) picritic ultramafic intrusions	Disseminated sulphides and native metals in herzolite, dunite, peridotite, etc.	Leckie Lake (<i>Wolf Mountain</i>); Hele Township; Eva-Kitto townships
Layered gabbro-anorthositic intrusions: Crystal Lake Gabbro	Disseminated and blebby sulphides in medium- to coarse-grained, varied-textured (<i>a.k.a.</i> 'taxitic') gabbro	Crystal Lake Gabbro (<i>Great Lakes Nickel deposit</i>)
	Disseminated sulphides in Cr-spinel-bearing cumulate layers	(<i>Cr-spinel-bearing, anorthositic gabbro above Cu-Ni deposit</i>)
Pine Point - Mount Mollie Gabbro	Disseminated, intergranular sulphides, fracture fillings	(<i>Mount Mollie; Pine River</i>)
Pigeon River and Arrow River diabase dykes	Disseminated sulphides in medium- to coarse-grained gabbro and diabase	(<i>Wallenius; Naomi Island; Jarvis Point</i>)

Reversed Magnetic Polarity
(ca. 1108 Ma):

Logan diabase sills, cone sheets	Sparse, disseminated sulphides	(Numerous)	
Tholeiitic to alkaline complexes: Coldwell alkaline complex Killala Lake alkaline complex	Disseminated sulphides in medium- to coarse-grained, vari-textured (<i>a.k.a.</i> taxitic) gabbro	Coldwell Two Duck Lake gabbro (<i>Marathon deposit</i>); Geordie Lake gabbro	Killala Lake Border gabbro (<i>Sandspit - Killala</i>)
	Disseminated sulphides in massive Fe-Ti-oxide cumulate layers	Eastern Border gabbro (<i>Skipper Lake zone</i>)	(<i>Unknown</i>)

The development of tectono-magmatic models for these various suites of intrusions is the focus of ongoing research as part of the Ontario Geological Survey's *Operation Treasure Hunt*. These new data will provide new insights into late Archean subprovince accretion in the Superior Province, as well as the development of the Midcontinent Rift. They will help to elucidate possible links between the age, geochemistry and setting of these intrusive rocks and PGE mineralization processes in order to generate new exploration targets.

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PLATINUM GROUP ELEMENT EXPLORATION IN NORTHWESTERN ONTARIO

SMYK, Mark C., STEWART, Jennifer and O'BRIEN, Mark S. Ontario Geological Survey,
Ministry of Northern Development and Mines, Suite B002, 435 James St. South, Thunder Bay,
ON P7E 6S7

During the past two years there has been a marked increase in exploration for the platinum-group elements (PGE) in northwestern Ontario. This interest has been driven by a dramatic rise in the prices of platinum and palladium. Renewed PGE exploration in northwestern Ontario has also been significantly influenced by the success of North American Palladium Ltd.'s Lac des Iles Mine which produced 95 116 ounces of palladium at a cash cost of US\$142 per ounce in 2000. Recent exploration efforts at Lac des Iles have increased the measured and indicated resource to 145 600 000 tonnes at an average grade of 1.57 g/t Pd, 0.17 g/t Pt, 0.12 g/t Au, 0.06 % Cu and 0.05 % Ni.

There were over 100 PGE exploration programs in northwestern Ontario in 2000, accounting for more than half of all mineral exploration in the region. These exploration efforts have focused on both Archean and Proterozoic mafic to ultramafic intrusions, leading to the discovery of many occurrences in areas and/or intrusions not previously known to host PGE mineralization.

PGE occur in two main geological settings:

- (1) In Archean pre- to post-tectonic, mafic to ultramafic intrusions. Mineralization may be associated with:
 - Disseminated "sparse" sulphides in gabbro and ultramafic rocks (*e.g.* Lac des Iles complex and satellite intrusive complexes), and localized by:
 - Zones of hydrothermal alteration
 - Heterolithic, igneous breccia zones
 - Contact zones and tectonic structures
 - (Semi-) massive, sheared, copper-nickel sulphide deposits (*e.g.* Shebandowan and Thierry mines) in ultramafic rocks
 - Sheared ultramafic rocks with copper-nickel sulphides intruding banded iron formation (*e.g.* Trout Bay)
 - Chromitite within layered ultramafic complexes (*e.g.* Big Trout Lake, Chrome Lake?)
- (2) In Mesoproterozoic, Midcontinent Rift-related (*ca.* 1108-1102 Ma), mafic to ultramafic intrusions near Lake Superior and Lake Nipigon. Mineralization may be associated with:
 - Disseminated sulphides in coarse-grained to pegmatitic, vari-textured ("taxitic") gabbro (*e.g.* Great Lakes Nickel; Marathon deposits)
 - Massive oxide ($\pm$ sulphide) units in layered gabbro (*e.g.* Coldwell Eastern Gabbro (Ti-Fe-oxides); Great Lakes Nickel (Cr-spinel))
 - Disseminated sulphide $\pm$ native metals in olivine-rich, layered ultramafic rocks (*e.g.* Wolf Mountain)

A NEW GRAVITY MAP OF WISCONSIN

SNYDER, Stephen L., U.S. Geological Survey, MS 954 National Center, Reston, VA 20192, ssnyder@usgs.gov; ERVIN, C. Patrick, Dept. of Geology and Environmental Geosciences, Northern Illinois University, DeKalb, IL 60115, pervin@niu.edu; GEISTER, Daniel W., Dept. of Geology and Environmental Geosciences, Northern Illinois University, DeKalb, IL 60115, z011561@students.niu.edu and DANIELS, David L., U.S. Geological Survey, dave@usgs.gov.

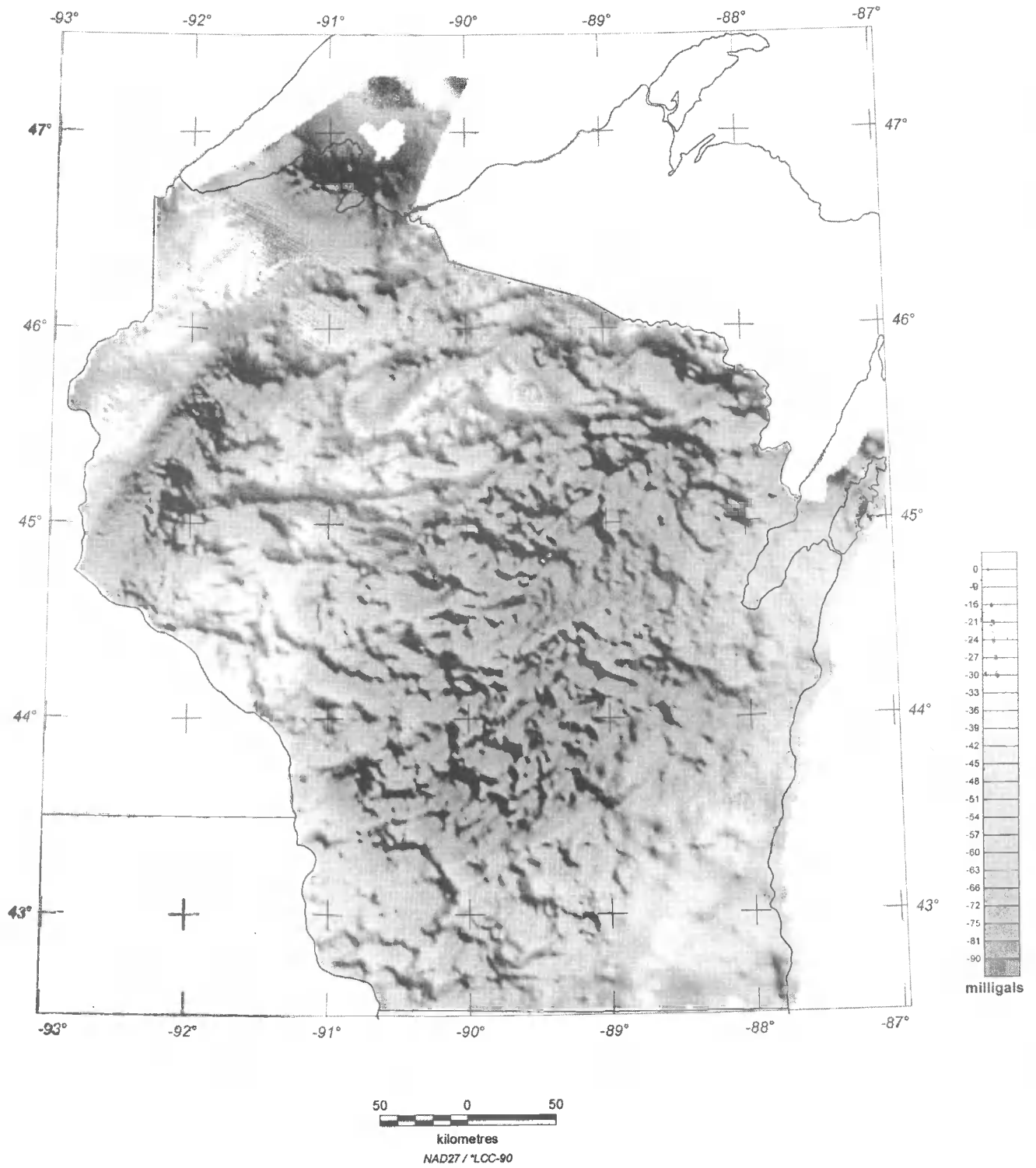
A new Bouguer anomaly gravity map of Wisconsin has been created from more than 37,000 gravity measurements collected between 1948 and 2000. North of latitude 44° N., more than 28,000 stations were compiled by C.P. Ervin and M.E. Thompson. These data include stations from the Wisconsin Geological and Natural History Survey (WGNHS), the National Geophysical Data Center (NGDC), the Defense Mapping Agency (DMA), the U.S. Geological Survey (USGS), and Northern Illinois University. An approximate station interval of 1 mile (1.6 km) was established where possible, but limited access in some areas necessitated a greater spacing.

Prior to 1999, the data south of latitude 44° N. totaled approximately 3800 stations from NGDC and from G. Randy Keller (University of Texas-El Paso). The current USGS effort, begun in 1999, is directed at upgrading the gravity coverage of the state south of latitude 44° N. with a station density comparable to that north of 44° N. To date we have added measurements at more than 6800 stations to achieve a nominal spacing of one to two miles. These new data replace the older data from the NGDC, which had a nominal station spacing ranging from 3 to 10 miles. Nearly all of the data are tied to the Wisconsin First-order Gravity Base Station Network, which is in turn tied to the International Gravity Standardization Network-1971 (IGSN-71). The 37,000 measurements were then gridded at an interval of 500 m. The map will be presented at a scale of 1:500,000.

The rationale for upgrading the gravity coverage has been to provide higher resolution data to assist in the interpretation of the basement geology of southern Wisconsin, much of which is hidden by glacial and Paleozoic cover. The gravity data, along with aeromagnetic data, give clues to the structural evolution of the Precambrian crust, making the map an excellent tool for USGS mineral resource studies.

Some notable features shown on this map include 1) the Midcontinent gravity high, which has one of the steepest gravity gradients in the conterminous US, 2) the flanking gravity lows corresponding to Keweenaw sedimentary basins, 3) gravity highs over inferred mafic plutons in southeastern Wisconsin, 4) a low centered on the Precambrian Wolf River batholith, but much larger in area, 5) gravity lows associated with granitic intrusives just south of latitude 46° N., and 6) several northwest trending linear features of unknown origin.

The accompanying figure shows a shaded relief image of the gravity map.



POST-RIFT EVOLUTION OF THE MIDCONTINENT RIFT SYSTEM: SOME NUMERICAL EXPERIMENTS

Soofi, M. A., and King, S. D., Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, Indiana 47907

The Midcontinent Rift system (MCR) is a major geological and geophysical feature of North America. This 1.1 b.y. old feature (Nicholson and Shirey, 1990; Klewin and Shirey, 1992) is believed to have evolved first through the tensile forces of a rift origin and then through the compressive forces from the intraplate collision between North America and Grenville Tectonic Zone (GTZ) (Van Schmus and Hinze, 1985). The support for interaction between the MCR and GTZ comes from the geophysical studies which reveal thrust faults and folds along the length of the MCR (e.g., Zhu and Brown, 1986; Chandler et al., 1989; Mariano and Hinze, 1994; Allen et al., 1997). Also, the time of thrusting along the MCR is constrained to be 1060 Ma (Bornhorst et al., 1988; Cannon et al., 1993) which is comparable to 1100-1060 Ma (Easton, 1992) as the duration of collision in Grenville Tectonic Zone.

A quantitative study of the late-stage deformation of the MCR under the Grenville tectonism has been performed by Soofi and King (1999). They showed that the distance between the MCR and Grenville Tectonic Zone is appropriate for the two geologic provinces to interact. We expand on their findings and investigate the contribution of various factors involved in the collision between North America and the Grenville terranes, including: the size of colliding terranes of Grenville Tectonic Zone; the location of collision along the eastern and southern boundaries of North America; and the angle of convergence between North America and the Grenville terranes. We use a 2D, viscous, finite element model that treats lithosphere as a thin sheet with stresses averaged over its thickness (for computational method see Houseman and England (1986); for program location see the web site <http://www.earth.monash.edu.au/Research/Basil>). The model boundaries coincide with pre-Grenville collision boundary of North America. In the model, the MCR is considered as a low-strength block. We consider the present shape of the MCR as the shape at the time of collision with the Grenville terranes. The models are run to represent 21 Ma of convergence at the rate of 50 mm/yr. To constrain the model results we use geophysically observed uplifts along the reverse faults of the MCR (e.g., Zhu and Brown, 1986; Mariano and Hinze, 1994; Allen et al., 1997). These uplifts are compared with crustal thickening along the MCR in the model.

Based on our results we conclude that the 3 to 8 km variation in uplift along the thrust faults of the western arm of the MCR is the consequence of size of the colliding terranes and location of the collision. The model results also suggest that deformation along the eastern arm of the MCR was comparable to that along the western arm. The reason we do not observe such deformation in geophysical studies (e.g., Zhu and Brown, 1986) is, perhaps, due to later surficial and/or tectonic processes. We also conclude that collision with Grenville Tectonic Zone was active along both the eastern and southern boundaries of North America. This resulted in the non-linear shape of the western arm of the MCR and may also played a role in the formation of the Belle Plaine fault. We do not observe any significant difference in the model results for different angles of convergence between North America and Grenville terranes. Consideration of other constraints in addition to the uplift along the MCR may help to determine the dominant angle of convergence between North America and Grenville Tectonic Zone.

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THE COOL EARLY EARTH: OXYGEN ISOTOPE EVIDENCE FOR CONTINENTAL CRUST AND OCEANS ON EARTH AT 4.4 Ga

VALLEY, JW*, PECK, WH, KING, EM, Dept. of Geology + Geophysics, Univ. of Wisconsin-Madison; GRAHAM, CM, Dept. of Geology + Geophysics, Edinburgh Univ., Scotland; and WILDE, SA, School of Applied Geology, Curtin Univ., Bentley, Western Australia, *valley@geology.wisc.edu

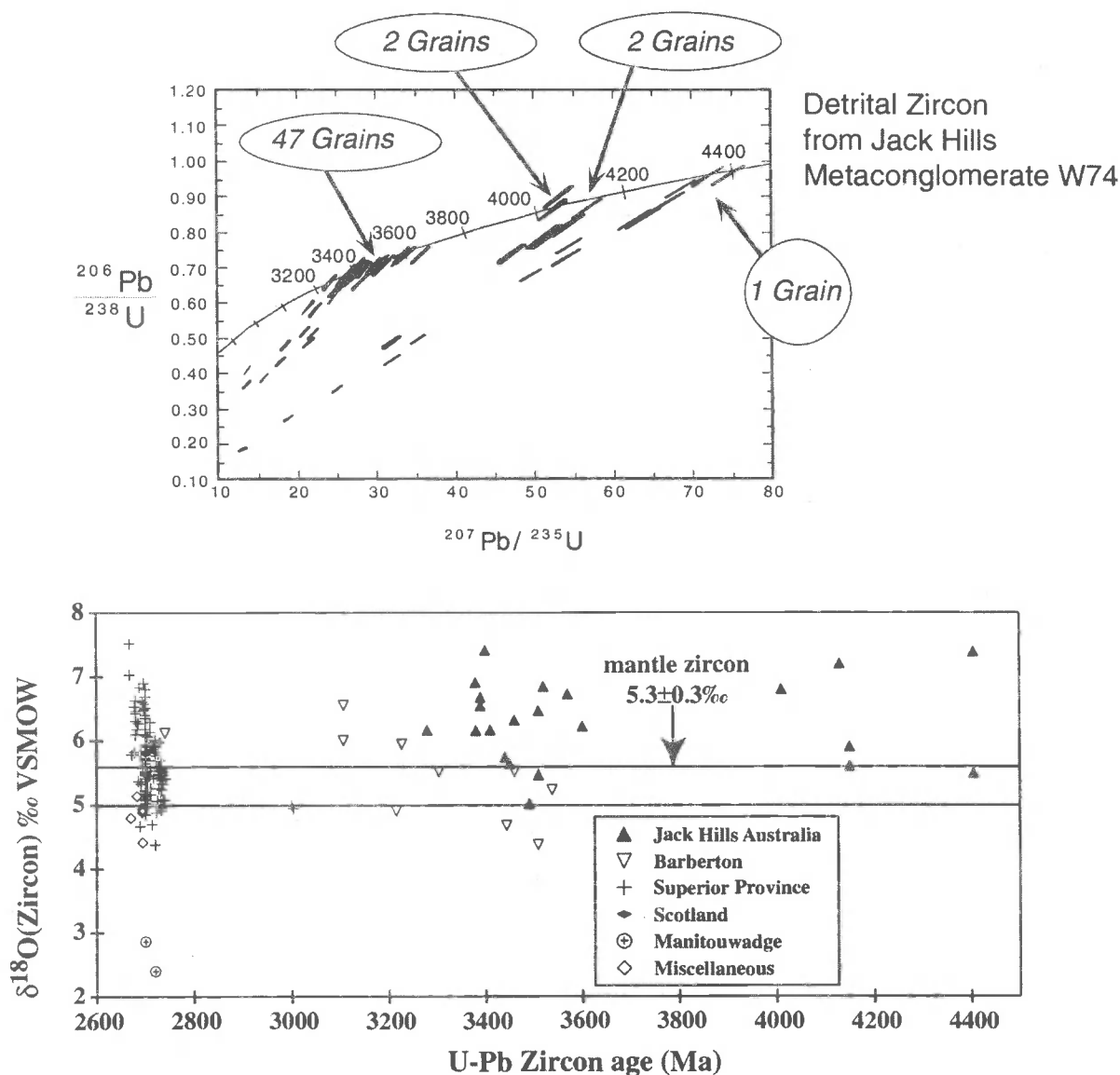
Zircons preserve the best record of U-Pb crystallization age and oxygen isotope ratios of igneous rocks. The $\delta^{18}\text{O}$ of non-metamict zircon is unaffected even by hydrothermal alteration and high-grade metamorphism.

Ion microprobe analysis of detrital zircons from the ~3 Ga Jack Hills metaconglomerate (Narryer Gneiss Terrane, Yilgarn Craton, Western Australia) yield U-Pb ages from 3.1 to 4.4 Ga (Fig. 1, SHRIMP II, ref 1) and $\delta^{18}\text{O}$ from 5 to 8 ‰ (Cameca 4f, ref 2). The $\delta^{18}\text{O}$ of these zircons averages 6.3, and is 1 per mil higher than that in equilibrium with the mantle and that of normal Archean granitic zircons (Fig. 2; 5.3 ± 0.3 ‰, 5.5 ± 0.4 ‰, respectively; ref 3). The distribution of mantle-like vs. mildly elevated $\delta^{18}\text{O}$ values for magmas is constant from 2.7 to 4.4 Ga, and on 4 continents (Fig. 2).

The age of 4.404 ± 0.008 Ga from one 200 μm zircon is >99% concordant and represents the oldest recognized terrestrial material. This crystal is zoned in $\delta^{18}\text{O}$ (5.0 ± 0.7 ‰ vs. 7.4 ± 0.7 ‰) and REEs (La=0.3 to 13.6 ppm), and contains inclusions of SiO_2 . REE patterns are HREE enriched with positive Ce and negative Eu anomalies; calculated melts are LREE enriched. Taken together, these results suggest crystallization from a quartz-saturated granitic magma and thus the existence of continental crust, possibly in a setting like Iceland. The high $\delta^{18}\text{O}$ portion of the crystal would be in equilibrium with a magma at $\delta^{18}\text{O}(\text{WR}) = 8.5\text{--}9.5$ ‰. There is no known mantle reservoir with such high values. $\delta^{18}\text{O}(\text{WR})$ values above 8.5 are typical of “S-type” granites that have melted or assimilated material that was altered by low temperature interaction with water at the surface of the Earth (i.e., weathering, diagenesis, low T hydrothermal alteration). Thus the high $\delta^{18}\text{O}$ value of the 4.4 Ga zircon suggests that surface temperatures were cool enough for liquid water suggesting that the early steam-rich atmosphere condensed to form oceans at that time.

The evidence for liquid water and oceans at 4.4 Ga suggests a Cool Early Earth. This contrasts with the Hot Early Earth and global magma oceans envisioned at 4.5–4.3 Ga based on: an impact origin of the Moon (4.45–4.50 Ga), core formation, higher Hadean radioactive heat production, and intense early meteorite bombardment (4). The surface of the Earth cools quickly to form a crust by radiation, but a magma ocean caused by these processes would persist beneath the initially thin crust for up to 400 m.y. (5) and might erupt as massive flood basalts in response to major meteorite impacts, boiling surface waters. The thermal contrasts presented by these lines of evidence are minimized if the Moon and core formed earlier (~4.5 Ga), if the Moon formed by a process not involving a Mars-size impactor, or if the early meteorite bombardment was less intense or irregular in timing. It is possible that periods of Cool vs. Hot Early Earth alternated, with

boiling of early oceans after major impact events followed by periods of cooler surface conditions. If life evolved in these seas, multiple extinctions before 3.9 Ga are suggested.



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NEW U-PB AGES FROM MINNESOTA, MICHIGAN, AND WISCONSIN: IMPLICATIONS FOR LATE PALEOPROTEROZOIC CRUSTAL STABILIZATION.

Van Schmus, W.R. (rvschmus@ku.edu) and MacNeill, L.C., both at Dept. of Geology, Univ. of Kansas, Lawrence, KS 66045, Holm, D.K., Dept. of Geology, Kent State University, Kent, OH 44242; and Boerboom, T. J., Minnesota Geological Survey, 2642 University Avenue, St. Paul, MN 55114.

As part of a comprehensive study of the East-Central Minnesota Batholith (ECMB: Boerboom and Holm, 2000; Van Schmus et al., 2000), we have also determined the U-Pb ages of several rock units spatially and (or) temporally related to it. The samples fall into several categories (Table 1): (a) the McGrath Gneiss to the NE of the ECMB in Minnesota; (b) Penokean basement east of the ECMB in Minnesota; (c) post-Penokean, pre-ECMB rocks in Michigan and Minnesota, and (d) units coeval with or slightly younger than the ECMB in Minnesota and Wisconsin.

Table 1. New U-Pb Results from Minnesota, Michigan, and Wisconsin.

Sample	Description	Age
MN00-07	McGrath Gneiss, 2 mi. west of McGrath, MN	2550 ± 14 Ma
MN00-01	Bradbury Creek granodiorite, 4 mi. south of Onamia, MN	1877 ± 15 Ma
MN00-02	Tonalitic gn., Hillman migmatite?, 3 mi. south of Onamia, MN	1853 ± 10 Ma
MN99-09	Late tonalite in Hillman migmatite, 3 mi. SE of Lastrup, MN	1798 ± 03 Ma
MN00-03	Late tonalite in Hillman migmatite, 9 mi. west of Onamia, MN	(composite of all 3 samples)
MN00-04	Late tonalite in Hillman migmatite, 13 mi. west of Onamia, MN	
AGR-1	Humboldt granite, Humboldt, MI (Holm et al., 2001)	1805 ± 07 Ma
Multiple	East Central Minnesota Batholith Van Schmus et al. (2000); Boerboom and Holm (2000) Includes EC-2, -4, -5, -15, and -25 of Jirsa and Chandler (1997)	1787 to 1772 Ma
PF-99	Two-mica granite, Park Falls, Wisconsin	1781 ± 14 Ma
VS73-37	Radisson Granite, Radisson, Wisconsin	1776 ± 08 Ma
VS73-08	Amberg granite, 1 mi. north of Amberg, WI	1754 ± 11 Ma
VS77-251	Lugerville granite, 1.5 mi. SW Lugerville, WI	1749 ± 04 Ma
VS79-85	Lugerville granite, Rock Carry Rapids, 1 mi. E Lugerville, WI	(pooled; all near concordia)
VS74-13	Observatory Hill rhyolite, 6 mi. south of Montello, WI	1759 ± 02 Ma
VS73-02	Montello granite, Montello, WI	1746 ± 03 Ma

The oldest sample is from the McGrath Gneiss and confirms the late Archean age of that unit. Two samples yielded Penokean ages. The Bradbury Creek granodiorite was dated by Goldich and Fischer (1986) at 1869 ± 5 Ma, and our date of 1877 ± 15 Ma is fully consistent with this. A tonalitic gneiss (MN00-02) about one mile to the north-northwest and mapped as Hillman migmatite yields a slightly younger, but statistically indistinct, age of 1853 ± 10 Ma. We are investigating the possibility that the Bradbury Creek unit is more extensive than originally defined from aeromagnetic data. In any case, normal Penokean ages occur in eastern Minnesota, and Penokean basement forms the host crust for the ECMB.

Several samples yielded U-Pb ages close to 1800 Ma. The main units in Minnesota are late, undeformed (or less deformed) tonalite phases within the Hillman migmatite complex. Samples from three separate localities yield a mean age of 1798 ± 3 Ma for the tonalite. For one of these samples (MN00-03), the tonalite dated intrudes deformed tonalitic gneiss similar to that of MN00-02. At this time it appears that the protolith for the Hillman migmatite may be Penokean, but that it was extensively injected by younger tonalite about 1800 Ma.

Further detailed sampling and geochronology will need to be done to test this option. In Upper Michigan an alkali-feldspar granite near Humboldt yielded an upper intercept age of 1805 ± 7 Ma (Holm et al., 2001). These rocks define a distinct post-Penokean, pre-ECMB phase of magmatism in or near the southern part of the Superior Province.

As reported previously (Van Schmus et al., 2000), the East-Central Minnesota Batholith was emplaced within a relatively short span of time 1787 to 1772 Ma. We analysed zircons from several drill core samples to the east (Jirsa and Chandler, 1997), and the results (Table 1: EC-2, EC-4, EC-5, EC-15, EC-25) extend the known area of the ECMB. In order to determine whether units of the so-called "1760 Ma" suite of rocks in Wisconsin are coeval with the ECMB, we reanalysed several samples from the senior author's collection, plus one new sample (PF-99) using single-grain analyses and more precise techniques. The westernmost samples (PF-99 and VS73-37) yield ages indistinguishable from those of the ECMB, suggesting that magmatism of that episode extended into northwestern Wisconsin. In contrast, samples of the "1760 Ma suite" farther east (Amberg and Lugerville granite) or farther south (Montello granite, Observatory Hill rhyolite) are distinctly younger, with ages of 1746 to 1759 Ma. These ages are similar to Ar-Ar ages reported for the ECMB and indicate that the last major magmatic pulse occurred about 1750 Ma.

Our new data now suggest three main post-Penokean pulses of magmatism about 25 m.y. apart in the southern Lake Superior region: ca. 1800, 1775, and 1750 Ma. The origin of the thermal energy in each case is presently unknown. These ages fall within the time span of magmatism in the Yavapai province-northern Central Plains orogen (inner accretionary belt; Van Schmus et al., 1993) and could correlate with pulses of northward directed subduction associated with southward growth of the continent. Interestingly, the two older and deeper-seated igneous bodies currently reside in Paleoproterozoic crust unaffected by younger Mazatzal deformation and reheating (Holm et al., 1998). It appears that localization of the earlier pulses in the west (Minnesota) and north (northwesternmost Wisconsin) may have contributed to the overall greater exhumation of these areas (compared to most of Wisconsin) and that this in turn may have dramatically strengthened the crust in those regions. We note that crustal remelting and thinning after orogenesis can both contribute to an overall stronger continental lithosphere. One final note: reference to a "1760 Ma" suite in Wisconsin should probably now be discontinued, since those rocks formed in two pulses at about 1775 and 1750 Ma.

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A STUDY OF WELL CONSTRUCTION FOR ARSENIC CONTAMINATION IN NORTHEAST WISCONSIN

ANNETTE E. WEISSBACH, Wisconsin Department of Natural Resources, DNR-Northeast Region, Waste Management, Remediation, and Redevelopment, 1125 N Military Ave, PO Box 10448, Green Bay WI 54307-0448

ELIZABETH M. HEINEN, Wisconsin Department of Natural Resources, DNR-Manitowoc Field Station, 2220 E CTH V, Mishicot WI 54228, and

KELD B. LAURIDSEN, Wisconsin Department of Natural Resources, DNR-Northeast Region, Waste Management, Remediation, and Redevelopment, 1125 N Military Ave, PO Box 10448, Green Bay WI 54307-0448

Arsenic has been detected in approximately one third of the private drinking water wells in the Fox River valley of Northeast Wisconsin. Concentrations detected are some of the highest found naturally occurring in the world. Research has indicated that presently 3.5% of the wells in Outagamie and Winnebago counties exceed the current drinking water standard of 50 ppb, whereas close to a quarter of the wells may exceed the proposed standard of 10 ppb.

Department of Natural Resources study results indicate the geochemical phenomenon causing the elevated levels of arsenic in groundwater of this region is associated with oxidation of a sulfide-mineralized zone located at the top of the deep sandstone aquifer system. A regional decline in water levels may have exposed this sulfide rich zone to oxidation from air within the open boreholes of water wells extending through this zone. This oxidation process can initiate a chemical reaction similar to acid mine drainage.

Recommendations have been developed for constructing wells within a delineated advisory area. This guidance recommends constructing wells with well casing pipe to extend through the sulfide rich zone. This study compared arsenic concentrations of wells constructed according to the guidance, with wells constructed to traditional construction standards. Additionally, this study examined data to determine if it was better to replace a contaminated well with a new one, or to reconstruct the existing well with a liner.

The results of this study indicate that the guidance gives adequate protection for wells constructed in the arsenic advisory area and that liners are successful at reducing arsenic concentrations, although not as successful eliminating arsenic contamination.

holes from which the samples were collected, and so may be from near the base of the Quaternary section. Low ppm Th / wt.% K ratios, which is the case for most of these high K tills, in general are indicators of potassic alteration. Because there is no apparent process that would create this type of alteration pattern following till deposition, it is proposed that tills with high K contents may have a local bedrock source area characterized by potassic alteration. This alteration may indicate pre-Marathon Formation paleoweathering of bedrock or may indicate local or regional hydrothermal alteration. Because potassic alteration can indicate precious metal and sulfide mineralization, high-K tills in the lower part of the Marathon Formation, characterized by some high Zn values, may aid in mineral exploration.

Provenance Discrimination

Samples of Quaternary deposits collected from closely spaced rotasonic boreholes in the area of the Bend massive sulfide deposit in Taylor County proved to have unique geochemical characteristics that could be explained by differences in source areas and sedimentological processes (Woodruff and others, 2000). The classification of till samples in the field was successfully duplicated by discriminate analysis of the geochemical data set using the statistical software package S+. Based on geochemistry and grain size, samples from the Bend area were statistically grouped into either Copper Falls or Marathon Formations, easily distinguishing a carbonate provenance and a Lake Superior provenance. The same type of discriminate analysis was run on the regional data set using identical element and grain size input. When compared to field classifications, results gave an error of 17% (correctly predicting 38 of 46 samples) for a carbonate provenance and an error of 5% (correctly predicting 51 of 54 samples) for a Lake Superior provenance. However, the utility of this statistical approach for the regional Quaternary data set is questionable. Geochemical fingerprints of correlated Mg and Ca values for samples from the Marathon Formation and correlated Cu and Ti for samples from the Copper Falls Formation identified in the Bend section are less distinct in the regional data set. Several factors inherent to the regional data, as compared to the Bend area data, may complicate correlations and discrimination of provenance. These factors include differences in the method of sample collection (rotasonic core vs. auger sampling), which could influence sample identification (e.g., till vs. glaciofluvial or glaciogenic debris samples), and the existence of geochemical outliers, such as the high K tills, in the regional data set that may reflect sampling from a larger geographic area with many diverse bedrock sources of material.

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