

# 71st Annual Meeting

*INSTITUTE ON LAKE SUPERIOR GEOLOGY*



## Proceedings Volume 71

### Part 1 – Program and abstracts

Mountain Iron, Minnesota, May 14-17, 2025



**71st Annual Meeting  
Institute on Lake Superior Geology  
Mountain Iron, Minnesota  
May 14-17, 2025**

***Meeting Co-Chairs***

Amy Radakovich, Allison Severson, Eric Nowariak, Stacy Saari, Aaron  
Hirsch

**Proceedings Volume 71  
Part 1: Program and Abstracts  
Edited by Co-Chairs**

# 71st Institute on Lake Superior Geology

## Volume 71 consists of:

### Part 1: Program and Abstracts

### Part 2: Field Trip Guidebook

**Trip 1:** Transect of the Quetico subprovince

**Trip 2:** Drill Core from three Cu-Ni deposits of the Duluth Complex

**Trip 3:** How do you make iron and/or manganese in Proterozoic Iron Formation?

**Trip 4:** New Geological Insights into the genesis of iron ores at Lake Vermillion – Soudan Underground Mine State Park

**Trip 5:** Neoarchean alkalic intrusions in the Wawa and Quetico subprovinces

**Trip 6:** Unique Keweenawan inclusion (Colvin Creek) in the Duluth Complex

**Trip 7:** Classic outcrops of Northeastern Minnesota

**Trip 8:** Glacial Lake Norwood and the Koochiching Lobe

### Reference to material in Part 1 & 2 should follow the examples below:

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Peter Hollings  
Department of Geology  
Lakehead University  
Thunder Bay, ON P7B 5E1  
CANADA  
peter.hollings@lakeheadu.ca

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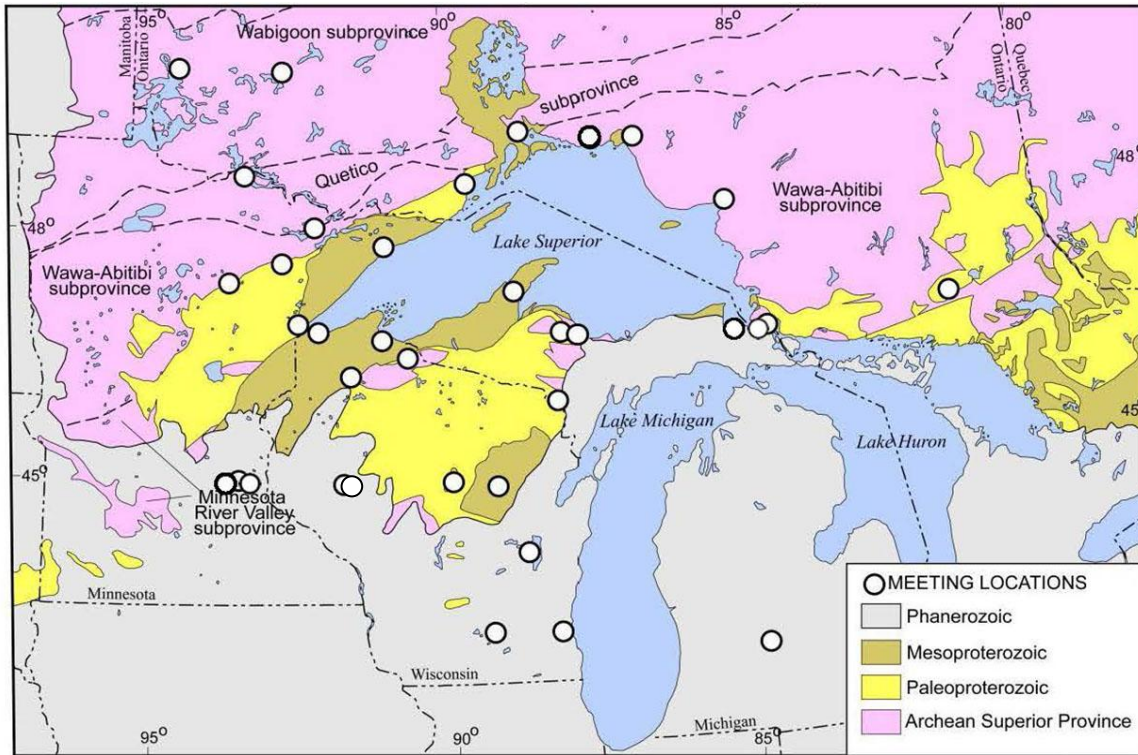
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## Institutes on Lake Superior Geology, 1955-2025



| #  | 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                 |

| <b>#</b> | <b>Date</b> | <b>Place</b>                   | <b>Chairs</b>                                            |
|----------|-------------|--------------------------------|----------------------------------------------------------|
| 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                            |
| 48       | 2002        | Kenora, Ontario                | P. Hinz & R.C. Beard                                     |
| 49       | 2003        | Iron Mountain, Michigan        | L. Woodruff & W.F. Cannon                                |
| 50       | 2004        | Duluth, Minnesota              | S. Hauck & M. Severson                                   |
| 51       | 2005        | Nipigon, Ontario               | M. Smyk & P. Hollings                                    |
| 52       | 2006        | Sault Ste. Marie, Ontario      | A. Wilson & R. Sage                                      |
| 53       | 2007        | Lutsen, Minnesota              | L. Woodruff & J. Miller                                  |
| 54       | 2008        | Marquette, Michigan            | T.J. Bornhorst & J. Klasner                              |
| 55       | 2009        | Ely, Minnesota                 | J. Miller, G. Hudak, D. Peterson                         |
| 56       | 2010        | International Falls, Minnesota | M. Jirsa, P. Hollings & T. Boerboom,<br>P. Hinz & M.Smyk |
| 57       | 2011        | Ashland, Wisconsin             | T. Fitz                                                  |
| 58       | 2012        | Thunder Bay, Ontario           | P. Hollings                                              |
| 59       | 2013        | Houghton, Michigan             | T.J. Bornhorst & A. Blaske                               |
| 60       | 2014        | Hibbing, Minnesota             | J. Miller & M. Jirsa                                     |
| 61       | 2015        | Dryden, Ontario                | R. Cundari & P. Hinz                                     |
| 62       | 2016        | Duluth, Minnesota              | J. Miller, C. Schardt & D. Peterson                      |

| #  | Date | Place                    | Chairs                                                         |
|----|------|--------------------------|----------------------------------------------------------------|
| 63 | 2017 | Wawa, Ontario            | A. Pace, A. Wilson & T.J. Bornhorst                            |
| 64 | 2018 | Iron Mountain, Michigan  | L. Woodruff, W. Cannon & E.K. Stewart                          |
| 65 | 2019 | Terrace Bay, Ontario     | P. Hollings & M.C. Smyk                                        |
| 66 | 2020 | Meeting cancelled        | Cancelled by the COVID-19 pandemic                             |
| 67 | 2021 | Virtual meeting          | M. Jirsa, M. Smyk & P. Hollings                                |
| 68 | 2022 | Sudbury, Ontario         | R.M. Easton & W. Bleeker                                       |
| 69 | 2023 | Eau Claire, Wisconsin    | R. Lodge, E.K. Stewart, & C. Ames                              |
| 70 | 2024 | Houghton, Michigan       | T.J. Bornhorst, E. Vye, P. Cobin, & J. Degraff                 |
| 71 | 2025 | Mountain Iron, Minnesota | A. Radakovich, A. Severson, E. Nowariak, S. Saari, A.C. Hirsch |

## Sam Goldich and the Goldich Medal

Sam Goldich received an A.B. from the University of Minnesota in 1929, a M.A. from Syracuse University in 1930, and a Ph.D. from the University of Minnesota in 1936. During World War II Sam worked for the U.S. Geological Survey in mineral exploration. In 1948, Sam returned to the University of Minnesota, and became Professor and Director of the Rock Analysis Laboratory the following year. He rejoined the U.S. Geological Survey in 1959 and was appointed as the first Branch Chief of the Branch of Isotope Geology. Sam returned to academia in 1964 when he went to Pennsylvania State University. He left PSU in 1965 and moved to the State University of New York at Stony Brook, where he stayed for 3 years. Restless yet again, he moved to Northern Illinois University in 1968 where he was a professor until his retirement in 1977. Sam's final move was to Denver where he became an emeritus at the Colorado School of Mines. Sam died in 2000, less than a month before his 92nd birthday.

In the late 1970s, Geological Society of America Special Paper 182, which included seminal geochronological studies by Sam Goldich and coworkers on the Archean rocks of the Minnesota River Valley, was nearing completion. At this time various ILSG regulars began discussing the possibility of recognizing Sam for his pioneering work on the resolution of age relationships and thus the geology of Precambrian rocks in the Lake Superior region. Three members, R.W. Ojakangas, J.O. Kalliokoski, and G.B. Morey, presented the idea to the ILSG Board of Directors in 1978. The Board approved the creation of an award, provided funding could be obtained. It was suggested that collecting one or two dollars at registration for a dedicated account would provide resources for striking the medal. A general request was made to the ILSG membership for donations and Sam himself offered a challenge grant to match the contributions. In total, \$4,000 was collected and thus began the work of creating the Goldich Medal.

The initial Goldich Award was presented to Sam by G.B. Morey in 1979 and consisted of a large paper proclamation. For the actual medal, G.B. Morey consulted with the foundry on production details, while Dick Ojakangas and Jorma Kalliokoski worked on the design of the award, suggesting that it be given for "outstanding contributions to the geology of the Lake Superior region." Simultaneously, a committee of J.O. Kalliokoski, W.F. Cannon, M.M. Kehlenbeck, G.B. Morey, and G. Mursky developed the Award Guidelines that were approved by the ILSG Board. By 1981 all the elements of the Goldich Award had come together, and the second recipient, Carl E. Dutton, Jr., received the Goldich Medal for 50 years of significant contributions to the understanding of the geology of the Lake Superior region. Since the beginning, the Awards Committee has consisted of individuals representing industry, government and academia, with each member of the Committee serving for three years. The medal is now awarded every year at the annual ILSG meeting.

### Reference:

Morey, G.B. and Hanson, G.N. (editors). 1980. Selected studies of Archean gneisses and Lower Proterozoic rocks, southern Canadian Shield. Geological Society of America, Special Paper 182, 175 p.

*Prepared by various Goldich Medal Awardees, 2007*



**Institute on Lake Superior Geology Goldich Medal**

# **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 vitas, 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    | 1998 | Zell Peterman         | 2016 | Mark A. Jirsa         |
| 1980 | <i>not awarded</i>   | 1999 | Tsu-Ming Han          | 2017 | Philip Fralick        |
| 1981 | Carl E. Dutton, Jr   | 2000 | John C. Green         | 2018 | Val W. Chandler       |
| 1982 | Ralph W. Marsden     | 2001 | John S. Klasner       | 2019 | Mark Severson         |
| 1983 | Burton Boyum         | 2002 | Ernest K. Lehmann     | 2020 | <i>not awarded</i>    |
| 1984 | Richard W. Ojakangas | 2003 | Klaus J. Schulz       | 2021 | Alan MacTavish        |
| 1985 | Paul K. Sims         | 2004 | Paul Weiblen          | 2022 | Terrence J. Boerboom  |
| 1986 | G.B. Morey           | 2005 | Mark Smyk             | 2023 | Peter Hollings        |
| 1987 | Henry H. Halls       | 2006 | Michael G. Mudrey     | 2024 | Suzanne W. Nicholson  |
| 1988 | Walter S. White      | 2007 | Joseph Mancuso        | 2025 | Robert Michael Easton |
| 1989 | Jorma Kalliokoski    | 2008 | Theodore J. Bornhorst |      |                       |
| 1990 | Kenneth C. Card      | 2009 | L. Gordon Medaris, Jr |      |                       |
| 1991 | William Hinze        | 2010 | William D. Addison &  |      |                       |
| 1992 | William F. Cannon    |      | Gregory R. Brumpton   |      |                       |
| 1993 | Donald W. Davis      | 2011 | Dean M. Rossell       |      |                       |
| 1994 | Cedric Iverson       | 2012 | James D. Miller       |      |                       |
| 1995 | Gene La Berge        | 2013 | Tom Waggoner          |      |                       |
| 1996 | David L. Southwick   | 2014 | Laurel Woodruff       |      |                       |
| 1997 | Ronald P. Sage       | 2015 | Rodney J. Ikola       |      |                       |

### 2025 GOLDICH MEDAL RECIPIENT

## Robert Micheal Easton

### Goldich Medal Committee

Serving through the meeting year shown in parentheses.

Dean Peterson (2022-2025) Big Rock Exploration, Industry Member (Committee Chair)

Marcia Bjornerud (2023-2026) Lawrence University, Academic Member

Robert Cundari (2025 - 2028) OGS, Government Member

## Citation for the 2025 Goldich Medal Recipient

### Robert Michael Easton



It is a great pleasure and honor to present the 2025 Goldich Medal to Dr. Robert Michael Easton, a highly respected senior scientist at the Ontario Geological Survey, in Sudbury, Ontario. Michael Easton, or ‘Mike’ as we know him, has been and is, without any doubt, among the leading and most productive geoscientists at the Geological Survey of Ontario (OGS) where he has spent much of his geological career (1982–2025). His *curriculum vitae* and publication list provide evidence for >600 publications and significant contributions — way too many to cite here. Even a short list of publications most relevant to the interests of the Institute and the geology of the Midcontinent Rift (MCR) spans four pages. The highlights include:

- a large number of peer-reviewed papers and reports;
- numerous extended abstracts in ILSG Proceedings volumes spanning the years from 1985 to 2023;
- meticulous editing of various ILSG Proceedings volumes; and
- the writing and editing of several comprehensive ILSG field trip guidebooks.

In 2022, Mike co-lead and co-organized the 68<sup>th</sup> *ILSG meeting in Sudbury*, the first post-“peak COVID” meeting. We had proposed organizing this Sudbury meeting years earlier, an idea cooked up at another ILSG meeting in Terrace Bay, ... but then COVID hit! It was a pleasure to organize this highly successful meeting with Mike, as one can always be 100% sure Mike will come through with everything. Although it was a joint effort, Mike took care of *all* the editing of both Proceedings volumes (Part I and II), and a fair bit of the local logistics.

Born and raised in Ontario, Mike started his geology career with a BSc Honours degree (1976) at the University of Western Ontario, London, with a thesis titled "*Geobotanical Studies in the Back River Volcanic Complex, NWT.*" He then moved on to the University of Hawaii, Honolulu, where he graduated (1978) with an MSc thesis on the "*Stratigraphy and Petrology of the Hilina Formation: The oldest exposed lavas of Kilauea Volcano, Hawaii.*" In the late 1980s, I remember studying a treatise and guidebook on volcanology that was influential at the time, and this was authored by Mike Easton and his wife Monica (Easton & Easton, 1985)!

Mike completed his graduate studies with a PhD from Memorial University (1982), in Newfoundland, with a thesis titled "*Tectonic Significance of the Akaitcho Group, Wopmay Orogen, NWT.*" These studies brought him to the Slave craton of northern Canada, and its western active margin, the Paleoproterozoic Great Bear Magmatic Zone. His studies of these ancient terranes, sponsored in part by the Geological Survey of Canada, prepared him well for the complex geology of the Canadian Shield in Ontario. He then joined the OGS, where over the years he has taken on more and more senior roles but never gotten away from doing fieldwork. At the OGS, Mike has mentored and supervised numerous students and junior colleagues, including a good number of them working in areas along the northern

shore of Lake Superior. He has also taken on more and more editorial roles for various OGS publications, maps, and datasets. From 2002 to 2007, Mike was one of the scientific leads of the *Lake Nipigon Geoscience Initiative* (LNGI), and provided oversight on OGS mapping projects in the region. He was directly involved in some of the mapping, and particularly the geochronology sampling. He handled numerous publications for this large project and was a guest-editor on the final volume that published many of the LNGI results (Easton et al., 2007). Since then, Mike has been a frequent collaborator on other projects either directly or indirectly relevant to Lake Superior area geology.

In the early 1990s, together with Terry Carter, Mike investigated the basement geology beneath the Paleozoic cover in SW Ontario (e.g., Easton & Carter, 1991, 1994, 1995), using geophysical data, and drill cores and cuttings, to locate the Grenville Front and the extension of the MCR in Ontario and into Michigan. Notably, they found that the Grenville Front was located some 100 km to the east of where previous interpretations had located it, and that metamorphosed equivalents of MCR rocks were likely present in the Grenville Front tectonic zone in Essex County. They were among the first to hypothesize that the final stages of MCR rifting and inversion were connected to the main tectonic phases of the Grenville orogeny.

From 2002 to 2010, Mike was involved with the MCR digital data and publication collaboration between the OGS, the Minnesota Geological Survey, and the United States Geological Survey, specifically the compilation of Ontario geological, mineral deposit, geochemical, and geochronological data in GIS-compatible formats to allow incorporation into the USGS-led cross-border compilation for the Midcontinent Rift. In addition, also in 2010, he was a co-organizer and editor of four guidebooks for the *11<sup>th</sup> International Platinum Symposium* (June 2010, Sudbury), a meeting that had a strong focus on the MCR, including a week-long field trip visiting deposits around Lake Superior. None of this would have ever happened without Mike's efforts and contributions. Among his many other contributions to ILSG over the years, Mike also served (and still serves) as a board member for the Institute (2022-2025).

After spending the last 53 summers doing fieldwork and research in the Grenville, the Southern Province, the Lake Superior area, or elsewhere in Ontario, Mike retired in March 2025. Given his outstanding accomplishments and amazing productivity over the years, either for the OGS or for various extra-curricular projects such as ILSG meetings, leading field trips, time-consuming editorial jobs, teaching as an adjunct professor, or supervising and mentoring many students (and never missing a beat!), it is a great honour to present Mike with the Goldich Medal

Citation by:

*Wouter Bleeker, Senior Research Scientist, Geological Survey of Canada, Ottawa*

# Honoring the Pioneers of Lake Superior Geology

*(Adopted by the Board of Directors, 2016)*

## Preamble

At the suggestion of Gene LaBerge, the 2016 executive board agreed to implement a program to recognize historic pioneers in the understanding of geology in the Lake Superior region. Beginning with the 2017 annual meeting, nominations will be accepted from the membership for geologists whose work was conducted primarily before the inception of the Institute in 1955. Biographical sketches of those pioneers will be presented at future annual meetings so that all may appreciate the value of their contributions. Selection of nominees will be decided in part by the organizing committee of each year's annual meeting, in consultation with the Board, to ensure equitable geographic representation in the selection process.

## Award Guidelines

- 1) Nominations from the membership will be submitted via the Institute web site and forwarded to the Chair of the next Annual Meeting. The nominations will be no more than half a page in length and will summarize the contribution of the nominee.
- 2) The Organizing Committee will select one or two individuals to be highlighted at the next Annual meeting and submit those names to the Board for approval.
- 3) The nominator will be requested to prepare a brief presentation to be given during the next annual meeting with a summary to be included in the Proceedings volume.
- 4) Unsuccessful nominations will be kept by the Secretary for two years and forwarded to the next meeting Chair; these nominations may be resubmitted at a later date.

*The Board will review this award every five years.*

## Pioneers of Lake Superior Geology

2017 Douglass Houghton (1809-1845)

2018-20 not presented

2021 Newton Horace Winchell (1839-1914)

2022 Thomas Leslie Tanton (1890-1971)

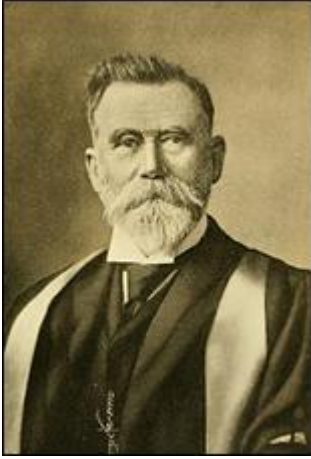
2023 Thomas Benton Brooks (1836-1900)

2024 Roland Duer Irving (1847-1888)

2025 Robert Bell (1841-1917)

## 2025 Citation for Robert Bell (1841-1917)

### Pioneer of Lake Superior Geology



Robert Bell had a decided taste for the natural sciences, especially for geology. In 1856, at the age of 15, he secured a temporary position with the Geological Survey of Canada. He assisted Sir William Logan, the Survey's Director, beginning an illustrious career with the GSC that would span half a century. While working summers for the Survey, Bell graduated in 1861 from McGill College and received the Governor General's Medal. Two years later, after study at the University of Edinburgh, he joined the faculty of Queen's College. All the while, he spent summers with the GSC and was made a permanent officer in 1869, named Assistant Director in 1877, Chief Geologist in 1890, and, finally, Acting Director in 1901. He also earned a medical degree in 1878 so that he was prepared for any mishap in the field.

Bell is best-remembered for his extensive explorations in northern Quebec, Ontario, Manitoba and the eastern Arctic in the 1870s and 1880s. He mapped the rivers between Hudson Bay and Lake Superior and reconnoitred part of the route that would be adopted for the National Transcontinental Railway. In 1859, Bell assisted in mapping the north shore of Lake Huron and first visited the Lake Superior region in 1860, west of Sault Ste. Marie. His *Report on the Geology of the Northwest Side of Lake Superior and of the Nipigon District* was published in 1870. In 1870 and 1871, he continued to work north of Lake Superior. In 1872 and 1873, he assisted GSC Director Alfred Selwyn on a preliminary exploration westward from Lake Superior to Fort Garry (now Winnipeg). In 1876, Bell examined the eastern shore of Lake Superior, as well as the Garden River and Echo Lake areas and the northeastern shore of Georgian Bay. A reconnaissance survey was undertaken between Parry Sound and the Ottawa River. In 1881, Bell carried out additional surveys in the Hudson Bay basin and in the Lake Superior region. During 1883 and 1884, Bell continued work near Lake of the Woods. In 1887, he continued a survey, started in 1886, between the Montreal River and Lake Huron to clarify the nature of the Huronian, especially in connection with its mineral deposits. He served as a member of the Royal Commission on the Mineral Resources of Ontario from 1888 to 1889. Between 1888 and 1892, Bell mapped the Sudbury and French River areas. His 1890 paper, *On Glacial Phenomena in Canada*, was regarded as the most significant advance in Canadian glaciology since Logan's first acceptance of glacial action in Canada in 1847. Bell was the first to recognize ice streaming in the Laurentide ice sheet and also noted the occurrence of diamonds in glacial drift from Ohio through Indiana, Michigan and Wisconsin, suggesting a possible provenance in Ontario.

Of particular interest to the ILSG is Bell's involvement on a Special Committee created in 1903 on the nomenclature and correlation of the Lake Superior region geology of the United States and Canada. Its findings led to the first joint report by geologists of the two countries. The Committee comprised C.R. Van Hise and C.K. Leith of the United States Geological Survey, A.O. Lane, State Geologist of Michigan; Robert Bell and Frank D. Adams of the GSC, and W.G. Miller, Provincial Geologist of Ontario. In August, 1904, the committee met in the Marquette district, and, during the six weeks following, visited the Gogebic, Mesabi, Vermilion, Rainy Lake, Lake of the Woods, Animikie, and

Huronian districts. As a result, both countries adopted a common stratigraphy and nomenclature that served as a basis for later iterations and our current stratigraphic framework.

Bell also made field notes on flora and fauna, forests, climate, soil, indigenous people, ethnology and resources. He performed much of his field work without maps and had to do topographical surveys as he went along. It is estimated that Bell named over 3000 geographical features, prompting colleagues to call him the “Father of Canadian Place-Names”. Bell authored 32 GSC reports, 111 journal papers, 17 solo-authored geological maps, 46 other geological, topographical, and cadastral maps as senior author, and 38 maps as junior author. He gave numerous lectures to natural history, historical, and charitable societies.

In 1865, at the age of 23, he was elected a fellow of the Geological Society of London. A charter-member of the Royal Society of Canada (1882), he became a fellow of the Royal Society of London in 1897. In 1903, he was made a companion of the Imperial Service Order and in 1906 was awarded both the Patron’s Medal of the Royal Geographical Society of London and the Cullum Geographical Medal of the American Geographical Society of New York.

Bell retired from the GSC in 1908. His career exemplified the wide-ranging reconnaissance work performed by the government geologist in the late 19<sup>th</sup> century. He was a generalist who valued field work over more detailed, specialized study. Few could match Bell’s travels, eclectic interests, and length of service. As Ami (1927) memorialized, “Bell was especially fond of investigating and exploring regions hitherto untraversed. Pioneer work of this nature can scarcely be appreciated today, when newer and more up-to-date methods of examining a hitherto-unknown territory are employed.”

*Citation by: Mark Smyk (Lakehead University / Ontario Geological Survey (retired))*

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## **In Memoriam James M. Franklin**

**(November 9, 1942 – June 19, 2024)**

We note the passing, on June 19, 2024, of long-term member and former SEG President (2000) James (Jim) M. Franklin. Jim had a long and productive career in academia, government, and industry. He made landmark scientific contributions to our understanding of volcanogenic massive sulfide (VMS) deposits, black smokers and sea-floor massive sulfide (SMS) deposits, and the metallogeny of the Precambrian orogenic belts.

Jim's work with the Ontario Department of Mines in 1966 along the north shore of Lake Superior led to his PhD study of the Proterozoic geology and metallogeny of the Thunder Bay area. He was the first Professor of Economic Geology at Lakehead University (1970–1976) and was later named as a Fellow of Lakehead University in 2017 in recognition of his many contributions to that institution and to its fledgling Geology Department. He then spent more than 20 years at the Geological Survey of Canada where he led the marine minerals program and ongoing work on VMS deposits on land, such as at Sturgeon Lake. Late in his career at the GSC, he was Chief Scientist and responsible for the day-to-day scientific direction of the organization and helping to inform and educate politicians and bureaucrats on the importance of science to the economy and well-being of Canada.

In 1998, after retiring from the GSC, he established Franklin Geosciences and had a highly successful career as a consultant and contributed to the discovery of mineral resources globally, while serving as a director and advisor to numerous companies and scientific organizations, including SEG.

Jim was very generous with his time and provided guidance and mentorship to students and professionals alike. He received numerous recognitions for his contributions, including Fellow of the Royal Society of Canada, member of the Canadian Mining Hall of Fame, and recipient of the Logan Medal recipient the Geological Association of Canada and the R.A.F. Penrose Gold Medal from SEG. He supported ILSG as field trip leader, Proceedings editor and banquet speaker.



## **In Memoriam**

### **Jorma "Joe" Kalliokoski**

(November 23, 1923 – June 3, 2024)

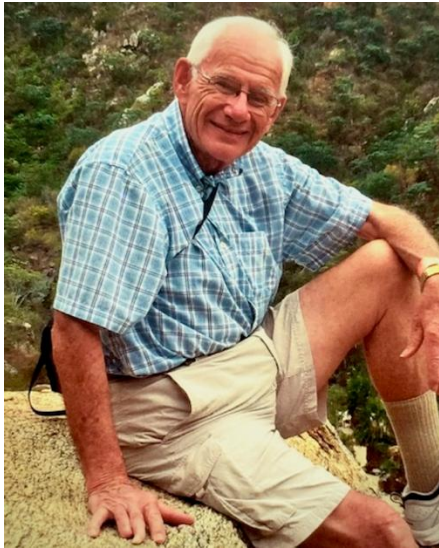
Jorma "Joe" Kalliokoski passed away on June 3, 2024, at age 100.

He was born in Harma, Finland on Nov 23, 1923. In 1931 his family moved to Sudbury, ON, and later to Timmins, ON. He graduated from Western University in London, ON, and later received his PhD from Princeton University.

Joe started as a geologist with the Geological Survey of Canada and later worked for Newmont Exploration. He was hired by Princeton's Department of Geology in 1956. In 1968, he moved to Michigan Tech as a Professor and Head of the Department of Geology and Geological Engineering, where he remained until his retirement in 1988. He was very proud of the department's growth in research papers and in research funding during his tenure. During his long geology career, he had many travel adventures from the wilds of Canada, to remote areas of South America, and various locations in Europe. He had the ability to make new friends everywhere he went.

Joe was a Fellow of SEG for a noteworthy 60 years, from 1958 to 2018. He served the Society in a number of volunteer positions, including SEG Councillor (1972–1974) and SEG President (1980). He served as Trustee of SEG Foundation, Associate Editor for Economic Geology, and Business Editor (1971–1977) and Director for the Economic Geology Publishing Company (PUBCO), the company that was established to publish the journal and later merged with SEG.

Joe was also an active member and supporter of ILSG, serving as its Secretary-Treasurer and Chair of the Goldich Medal Committee. He delivered papers at ILSG on various topics, including unconformity-type Proterozoic uranium deposit potential in northern Michigan; the Jacobsville sandstone and tectonic activity; and new Precambrian geology mapping of the Upper Peninsula. He Chaired the 1972 meeting in Houghton and was awarded the Goldich Medal in 1989.



## **In Memoriam**

### **James Alexander Grant**

(October 3, 1935 — October 3, 2024)

James Alexander Grant died on October 3, 2024 – coincidentally also his birthday – at the age of 89.

James “Jim” Grant was born in Inverness, Scotland, in 1935. After graduating from the University of Aberdeen, he left Scotland for Canada where he earned his M.S. at Queens University and then his Ph.D. at the California Institute of Technology (Caltech).

After graduating from Caltech, Jim took a job in Minneapolis as a geology professor with the University of Minnesota. Jim and his family moved to Duluth in 1969 and he joined the geology department at the University of Minnesota-Duluth, where he would work with his beloved colleagues and students for the next 35 years. In the early 1970s, he helped launch UMD’s still-running geology summer field camp in Park City, Utah, bringing undergrad students out to the mountains for many years. Jim’s groundbreaking work in the 1980s on the isocon diagram is now used by geologists the world over.

Over the course of his career, Jim made substantial contributions to the geology of the Lake Superior region. His seminal mapping of the Minnesota River Valley subprovince is still referenced today by the dozens who have since worked in the region. Jim taught hundreds of students over the course of his career who have gone on to contribute in many ways to the geology of the Lake Superior region. Among the most memorable experiences for his students were Jim’s metamorphic petrology trips through Michigan’s Upper Peninsula.

## **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 and Treasurer. Recipients will be announced at the end of the annual meeting.

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.

Successful applicants will receive their awards during the meeting.

## **Joe Mancuso Student Research Awards**

The 2005 Board of Directors established the ILSG Student Research Fund with \$10,000 US from the Institute's general fund to encourage student research on the geology of the Lake Superior region. A minimum of two awards of \$500 US each for research expenses (but not travel expenses) will be made each year. Students are expected to present their research orally or during a poster session at an ILSG meeting. The award winners will also be automatically eligible for the Eisenbrey Travel Awards. To allow the fund to grow, the Fund will receive one-half of any additional proceeds from each annual meeting, after all other commitments and expenses are covered.

- The ILSG Board of Directors will be responsible for selecting a minimum of two awards each year. The ILSG Treasurer will issue the awards.
- The ILSG Student Research Fund is available for undergraduate or graduate students working on geology in the Lake Superior region.
- The applications are due to the ILSG Secretary by August 31st of each year. Awards will be made by October 1st of each year.
- Names of the award recipients will be announced at the next annual meeting and posted on the ILSG website.
- Details of the application process can be found on the ILSG web site.
- The proposal will need to be signed by the researcher's supervisor.

The 2012 Board of Directors approved modification of the fund's name, adding "Mancuso" to reflect the many contributions of Joseph Mancuso to the organization and sizeable donations made in his name. "Doc Joe," as he was known by his students, taught geology for 36 years at Bowling Green State University, Ohio. He advised many graduate students in field-oriented research, and frequently brought them to Institute meetings. Joe was the 2007 Goldich Medalist.

In fall 2024, the ILSG Board of Directors selected two students to be granted research funding of \$500 each from the Joe Mancuso Student Research Fund. The awardees were:

**Zsuzsanna P. Allerton**, University of Minnesota- Twin Cities

**Omar Khalil Droubi**, University of Wisconsin - Madison

## **Doug Duskin Student Paper Awards**

Each year, the Institute selects the best of student presentations and honors the presenters with a monetary award. Funding for the award is generated from registrations of the annual meeting, and from generous donations to the fund in honor of Doug Duskin—an exploration geologist and long- time friend of the Institute. The 2012 ILSG Board of Directors approved adding Doug’s name to the award to acknowledge his contributions and distribute those donations in a manner that would have pleased him. The Duskin Student Paper Committee is appointed by the Meeting Chair. Criteria for best student paper—last modified by the Board in 2001—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 in conjunction with the Secretary, but typically is in the amount of about \$500 US (increase approved by Board, 10/01).
- 6) The Secretary 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.

### **2025 Student Paper Awards Committee**

**Aaron Hirsch** – Minnesota Geological Survey (Committee Chair)

**Carsyn Ames** – Wisconsin Geological and Natural History Survey

**Paula Leier-Englehardt** – HydroGeo Solutions LLC, Wisconsin

**Ross Salerno** – United States Geological Survey

**Esther Stewart** – Wisconsin Geological and Natural History Survey

**Nick Swanson-Hysell** – University of Minnesota

## **Board of Directors**

**Amy Radakovich**, Chair (2025-2028) - Minnesota Geological Survey

**Peter Hollings**, Secretary (2019-2027) — Lakehead University

**Mark A. Jirsa**, Treasurer (2022-2025) — Minnesota Geological Survey

**Mike Easton** (2022-2025) — Ontario Geological Survey

**Carysn Ames** (2023-2026) — Wisconsin Geological and Natural History Survey

**Theodore J. Bornhorst**, (2024-2027) — Michigan Technological University

Board members serve through the close of the meeting year shown in parentheses.

## **2025 ILSG Meeting Volunteers**

**Angela Sipila** - Mesabi Range Geological Society

**Henry Djerlev** - Mesabi Range Geological Society

**Kim Berry** - Mesabi Range Geological Society

**William Daniels** - Mesabi Range Geological Society

**Ann Marie Prue** - MN Department of Natural Resources

## **2025 ILSG Meeting Session Chairs**

**Aaron Hirsch**, Minnesota Geological Survey

**Robert Lodge**, University of Wisconsin, Eau Claire

**Eric Nowariak**, Minnesota Geological Survey

**Amy Radakovich**, Minnesota Geological Survey

**Stacy Saari**, Minnesota Department of Natural Resources, Lands and Minerals

**Allison Severson**, Minnesota Geological Survey

## Field Trip Leaders and Guidebook Authors

Field trips have been the mainstay of the ILSG since its inception 71 years ago. We give special thanks to the field trip leaders and guidebook authors who volunteered their time and talent in carrying that tradition forward.

**Trip 1:** Transect through the Quetico subprovince of northern Minnesota – Eric Nowariak (Minnesota Geological Survey), Mark Jirsa (Minnesota Geological Survey, retired)

**Trip 2:** Drill Core from three Cu-Ni deposits of the Duluth Complex - Mark Severson (Natural Resources Research Institute, Teck Retired), Cullen Phillips (New Range Copper Nickel), Kevin Boerst (Twin Metals Minnesota)

**Trip 3:** How do you make iron and/or manganese in Proterozoic Iron Formation? - Alex Steiner (Big Rock Exploration), Latisha Brengman (University of Minnesota, Duluth), Dean Peterson (Big Rock Exploration)

**Trip 4:** New Geological Insights into the genesis of iron ores at Lake Vermillion – Soudan Underground Mine State Park - George J. Hudak (University of Minnesota, George Hudak Geosciences P.L.L.C.), Zsuzsanna P. Allerton (University of Minnesota), Annia Fayon (University of Minnesota)

**Trip 5:** Neoproterozoic alkaline intrusions in the Wawa and Quetico subprovinces - Terry Boerboom (Minnesota Geological Survey, retired), Amy Radakovich (Minnesota Geological Survey)

**Trip 6:** Unique Keweenaw inclusion (Colvin Creek) in the Duluth Complex - Mark Severson (Natural Resources Research Institute, Teck, retired), Allison Severson (Minnesota Geological Survey), Lauri Severson (Earth Science teacher, retired)

**Trip 7:** Classic outcrops of Northeastern Minnesota - Dean M. Peterson (Big Rock Exploration), George J. Hudak (University of Minnesota, George Hudak Geosciences P.L.L.C.)

**Trip 8:** Glacial Lake Norwood and the Koochiching Lobe - Phillip Larson (Vesterheim Geoscience PLC), Andrew Breckinridge (University of Wisconsin-Superior), Howard Mooers (University of Minnesota, Duluth)

# Mine to Mountain Bike Mecca: The story of the Redhead Mountain Bike Park

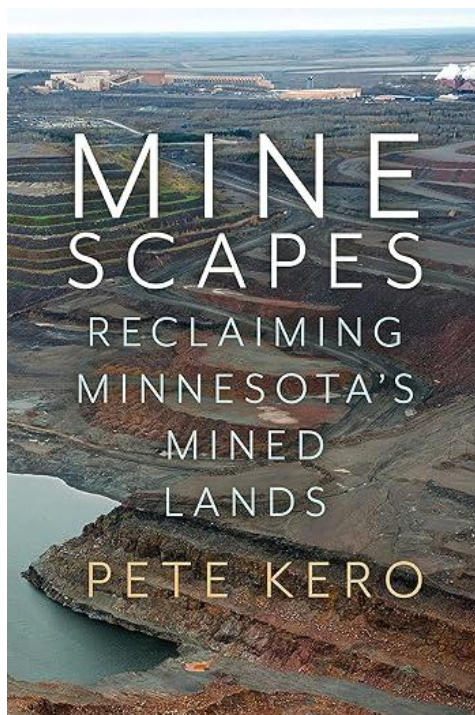
Pete Kero

PE, Senior Environmental Engineer

Barr Engineering Co.

**Pete Kero, PE**, is an environmental engineer and Vice President with Barr Engineering Co. He has over 30 years of experience in mine permitting, water management, reclamation, and repurposing across the United States. He was the visionary behind the award-winning Redhead Mountain Bike Park in Chisholm, Minnesota which repurposed several former iron mine pits and stockpiles into a destination-quality regional park for mountain biking, hiking, water recreation and all-terrain vehicles. The project has been featured by Outside Magazine, the Sierra Club and the nation-wide documentary film Biketown. Pete's book *Minescapes: Reclaiming Minnesota's Mined Lands*, which was published by the Minnesota Historical Society Press, won a 2024 Minnesota Book Award.

This talk will describe the transformation of ten idled open pit iron ore mines in northeastern Minnesota into a world-class recreation destination for mountain biking, hiking and paddling. In addition to describing how and why the trails were built, the presentation will include technical details on sustainable trail design, the concept of intermediate recreational use, changes to mine pit fencing laws that allow for government-sanctioned recreational use of mine lands and the early results and benefits from the first 5 years of the park's operation.



# Report of the Chairs of the 70<sup>th</sup> Annual Meeting

Theodore J. Bornhorst, Erika C. Vye and Patrice F. Cobin

## Houghton, Michigan

The 70<sup>th</sup> Institute on Lake Superior Geology (ILSG) was held May 15 to 18, 2024 in Houghton, Michigan, with the meeting headquartered at the Memorial Union Building on the campus of Michigan Technological University. The meeting was sponsored by the A. E. Seaman Mineral Museum, the Great Lakes Research Center, and the Department of Geological and Mining Engineering and Sciences - all units of Michigan Technological University. The meeting was co-chaired by Ted Bornhorst (principal co-chair), Erika Vye, Patrice Cobin, and Jim DeGraff; all co-chairs are affiliated with Michigan Technological University. In addition to being a co-chair Patrice Cobin and Julie Stark served as registrars for the 70<sup>th</sup> annual meeting. The institute was attended by a total of 182 participants of which 40 were students.

The meeting consisted of two full days of technical sessions from Thursday morning 16<sup>th</sup> of May through Friday afternoon 17<sup>th</sup> of May, and two days for field trips, pre-and post-meeting. A total of 57 presentations were subdivided into 8 technical sessions; 6 technical sessions for 30 oral presentations (of which 5 were presented by students), and 2 poster technical sessions with a total of 27 poster presentations (of which 16 were presented by students). Three presentations were withdrawn. Since past meetings have not included a dedicated technical session for poster presentations, the chairs opted to include two poster sessions for the 70<sup>th</sup> meeting. We believe this facilitated more time for attendees to review the posters and facilitated interaction between the authors of posters and attendees. The technical sessions of the 70<sup>th</sup> annual meeting of ILSG were published in 2024 as Part 1 of Proceedings Volume 70 (111 pages).

As is customary with ILSG meetings, the field trips were a highlight of the 70<sup>th</sup> ILSG. The meeting offered 7 field trips with 3 pre-meeting on Wednesday May 15, and 4 post-meeting trips on Saturday May 18. Overall, the field trips were well attended. There were 145 registrants for the 5 field trips that were able to be run. Demand for 4 of the trips exceeded capacity resulting in wait lists.

Pre-meeting trip 1 was led by Ted Bornhorst (Michigan Tech) and focused on *Mesoproterozoic "Midcontinent Rift-filling Strata and Native Copper Deposits of the Keweenaw Peninsula, Michigan."* Pre-meeting trip 2 was led by Tom Wright (Quincy Mine Hoist Association) and Jim DeGraff and Katherine Langfield (Michigan Tech) and focused on the *"Mining History and Geology of the Quincy Mine, Keweenaw Peninsula Native Copper District, Michigan."* Pre-meeting trip 3 focusing on *"Geoheritage of Buffalo Reef: Industrial Impact on Land, Culture, and Fish Sovereignty"* was scheduled to be led by Erika Vye, Charlie Kerfoot (Michigan Tech), Stephanie Swart (Michigan Department of Environmental Quality), and Dione Price and Evelyn Ravindran (Keweenaw Bay Indian Community). However, the trip could not be run because of low water levels and shifting sediment impeding access to the harbor.

Post-meeting trip 4 was led by Jim DeGraff, Katherine Langfield, and Dan Lizzadro-McPherson (Michigan Tech) and focused on “*Keweenaw Fault Geometry and Kinematics: Clues to Its Nature and Origin.*” Post-meeting trip 5 was led by Matt Portfleet (Adventure Mining Company) and Ted Bornhorst (Michigan Tech) and focused on the “*Adventure Mine, Ontonagon County, Michigan: Geology and History of a Native Copper Mine.*” Post-meeting trip 6 led by Chad Deering (Michigan Tech) ventured outside of the Keweenaw rift to investigate “*Southern Complex Granitoids, Gneisses, and Migmatites: New Data, Discoveries, and Perspectives.*” Field trip 7 led by Stan Vitton and Mohammad Sadeghi (Michigan Technological University) was scheduled to investigate “*Landslides in the Glacial Lake Ontonagon Sediments,*” but had to be cancelled due to lack of registrations. Field trip guides were published in 2024 as Part 2 of the Proceedings Volume 70 (194 pages).

Five Doug Duskin Best Student Paper Awards were given for student oral and poster presentations as judged by the 2024 Student Paper Awards Committee chaired by Stacy Saari (Minnesota Department of Natural Resources). Zsuzanna Allerton was awarded the best oral presentation. The best graduate student poster presentation was awarded to Yirou Xu. The best undergraduate student poster presentation was awarded to Lyndsie Vickers. Alice Martin and Alexander Lawrence were awarded the runner-up for graduate student poster and for undergraduate student poster respectively.

The 70<sup>th</sup> ILSG awarded 14 Student Travel and Participation Awards to help defray the cost of presentations of their research and participation in the ILSG professional meeting. The eligibility of costs, as designated by the Eisenbrey Award, were expanded for the 70<sup>th</sup> ILSG Student Travel and Participation Awards. We thank the donors for supporting the student awards. The awards were made possible by the generous financial support from our corporate sponsor Eagle Mine – Lundin Mining, the Geological Society of Minnesota, and 23 individual donors. The awardees were Zsuzsanna Allerton, Farhan Ahmed Bhuiyan, Andrea Paola Corredor Bravo, Kevin Mexia Duran, Trent Ediger, Alex Lawrence, Jordan Peterzon, Lucas Robarg, Daniel Shakked, Vlad Sheshnev, Demily Thibodeau-Bello, Adam Vanderkin, Lyndsie Vickers, and Yiruo Xu. There were 6 Michigan Tech students whose registration fees were waived because they volunteered with logistics for the meeting.

The ILSG social and banquet was hosted at the Memorial Union Building on Thursday evening May 15. There were 120 people at the annual banquet. Ted Bornhorst served as master of ceremonies for the post-banquet program. After the introductions, Peter Hinz gave a short presentation about a geological excursion to Hawaii. Amy Radovich announced the location of the 2025 meeting as Mountain Iron. The program continued with ILSG awarding the prestigious Goldich Medal to Suzanne W. Nicholson (recently retired from the U.S. Geological Survey). Laurel Woodruff (U.S. Geological Survey and Goldich Medalist in 2014) provided the citation for Suzanne. The co-chairs and the A. E. Seaman Mineral Museum recognized Ted Bornhorst with a plaque for his distinguished service to ILSG. A highlight of the banquet was the keynote presentation by Robert Hazen (Carnegie Institution for Science), an internationally recognized and distinguished mineralogist. His thought-provoking presentation was on “*Mineral Informatics: A New Frontier in Understanding Earth.*” The keynote presentation ended the banquet program. Hazen’s presentation was made possible by joint funding between the 70<sup>th</sup> ILSG and the A. E. Seaman Mineral Museum of Michigan Tech. Hazen gave a second presentation on Friday evening for the general public and as a bonus for ILSG participants. This presentation was the A. E.

Seaman Mineral Museum's 2024 Edith D. and E. Wm Heinrich Lecture titled "*Mineral Evolution: A case study of a new natural law.*"

The first presentation of the technical sessions was given by Jim Miller (Goldich Medalist in 2012) who gave the citation for Roland Duer Irving as the 2024 Pioneer of Lake Superior Geology. Irving is the 5<sup>th</sup> person to be recognized for their contributions to Lake Superior Geology prior to the initiation of the ILSG.

The Institute's Board of Directors met on Thursday May 16, 2024 to discuss ILSG business and approve the 2025 meeting location. The meeting was attended by Ted Bornhorst (Board Chair), Carysn Ames, Mark Smyk, Peter Hollings (Secretary), and Mark Jirsa (Treasurer). Guests at the meeting were the meeting co-chairs Patrice Cobin, Erika Vye, and Jim DeGraff, and Amy Radakovich (Assistant Treasurer) and also the Chair of the proposed 2025 Mountain Iron meeting (approved by the board see below). Stacy Saari, Alli Severson, Eric Nowariak, and Aaron Hirsch were additional guests supporting the proposed Mountain Iron 71<sup>st</sup> ILSG.

Institute's Board of Directors meeting notes were taken by ILSG Secretary Hollings, which are as follows:

1. Accepted report of the Chairs for the 69<sup>th</sup> ILSG, as published in the Proceedings volume, and minutes of last Board meeting, May, 2023 (Hollings).
2. Received, discussed, and accepted 2023-2024 ILSG Financial Summary (Jirsa).
3. Received, discussed, and accepted 2023-2024 report of the Secretary (Hollings).
4. Approved Ted Bornhorst as on-going ILSG Board member and Amy Radakovich as Chair.
5. Discussed and approved replacing Dorothy Campbell as the "member from government" on Goldich Committee (end of term 2024) with Robert Cundari.
6. Approved Mt Iron as the site for the 71<sup>st</sup> annual ILSG meeting. The meeting will be Chaired by Amy Radakovich and hosted by the Minnesota Geological Survey.
7. A number of future meeting locations were discussed. Peter Hinz has offered Kenora as a future site, while Mark Puumala has offered Thunder Bay.
8. The confusion over the appointment of the Board Chair was discussed and it was agreed we would follow the Constitution with the incoming Meeting Chair assuming the role of Board Chair.
9. It was agreed that the purchase of additional safety equipment would be postponed for now.
10. The Secretary agreed to revamp the boilerplate material for the volumes to make it easier for the organisers of subsequent meetings. Carsyn agreed to revamp the Eisenbrey and Mancuso award applications. Bornhorst agreed to rewrite the Eisenbrey award document for Board consideration. The allowable expenses will be broadened so the award will be more than travel.
11. Discussed and approved renewal of Pete Hollings as Institute Secretary (end of term 2027). This was later approved by a vote of the membership.
12. Hollings mentioned that the ILSG proceeding volumes standing order sales remain the same as the recent past with only 5 institutions receiving them plus one sent to GeoRef.

13. The co-Chairs would like to thank all those who helped make the 70<sup>th</sup> annual meeting a success such as judging student papers, chairing sessions, leading field trips, driving for field trips, staffing the registration desk, caring for the projectors, general logistics and more. A special thank you goes to Julie Stark, who played a key role in online and onsite registration.

The 70<sup>th</sup> ILSG was a milestone for a professional organization, as noted by Pete Hollings in a recently published article on ILSG in the Lake Superior Magazine - *“not a lot of groups hang around 70 years.”* Forty years ago, Ted Bornhorst chaired the annual meeting and Board of Directors. At this time the board had serious concerns about the survival of the organization. We are happy to report that ILSG continues to thrive and has done so by being a small, but vibrant organization. We believe that the combination of collegial, friendly, and open discussion and exchange of ideas on geology of the Lake Superior region between government, industry, and academic geologists has played a major role in ILSG’s survival for 70 years. We strongly believe that field relations are the foundation of geologic interpretation. The depth, breadth, and quality of ILSG field trips is another reason ILSG continues to thrive. What makes ILSG field trips special is that trip leaders are open to debate on their interpretation of an outcrop. Open - but not competitive - discussion is a hallmark of both ILSG field trips and technical sessions. Lastly, meetings would not be possible without people willing to serve as chair or co-chair and people willing to organize the annual conference, to lead field trips, and to serve on local committees. Chairing an ILSG meeting involves personal time, extra work, and a bit of extra stress as attested to by anyone who has risen to this challenge in past years. One of us (Bornhorst) has been principal chair for 6 meetings over 41 years, from 1983 to 2024. He agreed to be Chair one last time to mentor Erika and Patty with the hope that one day, one or both of them, will chair a future annual meeting, contributing to the continuation of ILSG. We hope that ILSG survives for many decades and into the next century and beyond.

We are gratified by the positive comments by participants and are happy to have served the Lake Superior geological community. We look forward to the 2025 Mountain Iron ILSG meeting when we can be much more relaxed!

Respectfully submitted,

Theodore (Ted) Bornhorst, Erika Vye, and Patrice (Patty) Cobin  
Co-chairs, 70<sup>th</sup> Institute on Lake Superior Geology

**Donations to Support the Annual Meeting of the  
Institute on Lake Superior Geology**



Swenson College of Science and Engineering  
**Earth and Environmental Sciences**

**A special thank you to our individual contributors**

Roger Anderson

Allan MacTavish

Dave Dahl

# **Donations to Support Student Participation at the Annual Meeting of the Institute on Lake Superior Geology**

**A special thank you to our individual contributors**

Kate Clover

Jim and Isagel DeGraff

Tom Erickson

Tom Fitz

Aaron Hirsch

Paula Leier-Engelhardt

Bob Mahin

Vince and Susan Mathews

Jim Miller

Allison Severson

Mark and Lauri Severson

John Verhoeven

Gerry White

# TECHNICAL PROGRAM

## **Wednesday May 14, 2025**

All field trips begin and end at the Mountain Iron Community Center

### **Pre-meeting Field Trips May 14, 2024**

8:00 am - 5:00 pm **PRE-MEETING FIELD TRIPS**

**Trip 1:** Transect through the Quetico subprovince of northern Minnesota – Eric Nowariak (Minnesota Geological Survey), Mark Jirsa (Minnesota Geological Survey, retired)

**Trip 2:** Drill Core from three Cu-Ni deposits of the Duluth Complex - Mark Severson (Natural Resources Research Institute, Teck Retired), Cullen Phillips (New Range Copper Nickel), Kevin Boerst (Twin Metals Minnesota)

**Trip 3:** How do you make iron and/or manganese in Proterozoic Iron Formation? - Alex Steiner (Big Rock Exploration), Latisha Brengman (University of Minnesota, Duluth), Dean Peterson (Big Rock Exploration)

**Trip 4:** New Geological Insights into the genesis of iron ores at Lake Vermillion – Soudan Underground Mine State Park - George J. Hudak (University of Minnesota, George Hudak Geosciences P.L.L.C.), Zsuzsanna P. Allerton (University of Minnesota), Annia Fayon (University of Minnesota)

## **Wednesday evening May 14, 2025**

5:00 pm - 8:00 pm **Registration** (Mountain Iron Community Center)

6:00 pm - 8:00 pm **Poster Setup and Viewing** (Mountain Iron Community Center)

6:00 pm - 8:00 pm **Welcoming Reception** (Mountain Iron Community Center)

\* Denotes a student eligible for Best Student Paper Award. To be eligible students must have graduated no more than one month before the ILSG meeting, be first author, and present the paper at the meeting

+ Denotes author that will present the paper if different than the first author.

## **Thursday - May 15, 2025**

7:15 am – 12:00 pm **Registration** (Mountain Iron Community Center)

8:00 am. **Opening remarks** (Mountain Iron Community Center)

Amy Radakovich, Allison Severson, Eric Nowariak, Stacy Saari, Aaron C. Hirsch  
Co-Chairs, 2025 ILSG

## TECHNICAL SESSION I – ORAL PRESENTATIONS

*Session Chair: Amy Radakovich*

8:20 **Mark SMYK**

*Robert Bell - Pioneer of Lake Superior geology*

8:40 **William J. HINZE and Mark B. LONGACRE**

*Revisiting Gravity and Magnetic Anomalies of the Baraboo Range*

9:00 **Huifang XU and Tianyu ZHOU**

*Battle between the bands: competitive precipitations lead to bands in banded iron formations*

9:20 **Howard MOOERS, Mark SEVERSON, Peter JONGEWAARD, and Phillip LARSON**

*US Steel Corporation / Ralph W. Marsden iron ore collection*

9:40 **Matt CARTER**

*Updates on the Minnesota Department of Natural Resource's Drill Core Library*

10:00 **END OF TECHNICAL SESSION I**

10:00-10:20 **COFFEE BREAK**

## TECHNICAL SESSION II – ORAL PRESENTATIONS

*Session Chair: Stacy Saari*

10:20 **Alan AUBUT**

*A Contrarian View: Thoughts on the Genesis of the Tamarack Ni-Cu Deposit*

10:40 **Cory PALIEWICZ and Joyashish THAKURTA**

*Lithogeochemical Characterization of Manganese Mineralization at the Cuyuna Range, Central Minnesota*

11:00 **Guy N. EVANS and William E. SEYFRIED JR.**

*Experimental Reproduction of Acidic Mafic-Ultramafic Hydrothermal Fluids with Implications for Linking Seafloor Lithology to Ore Mineral Solubility and Novel Geochemical Trapping Mechanisms*

11:20 **Wyatt BAIN, James TOLLEY, and Peter HOLLINGS**

*An overview of the geology, tectonic setting, and occurrence of sulphide mineralization in the Lac Des Iles Intrusive Suite*

11:40 **Thomas BUCHHOLZ, Alexander FALSTER, and William SIMMONS**

*A complex F-rich alkalic pegmatite in the pyroxene syenites of the stettin complex, Wausau Complex, Marathon county, Wisconsin*

12:00 **END OF TECHNICAL SESSION II**

**12:00-1:30 LUNCH BREAK and ILSG BOARD OF DIRECTORS MEETING**

- Buffet lunch provided-

**TECHNICAL SESSION III- POSTER PRESENTATIONS**

*Session Chair: Robert Lodge*

**1:30-3:00      AUTHORS PRESENT AT THEIR POSTERS**

**2:40-3:00      COFFEE BREAK**

**3:00      END OF TECHNICAL SESSION III**

**TECHNICAL SESSION IV – ORAL PRESENTATIONS**

**Session Chair: Allison Severson**

**3:00 James V. JONES, Ross SALERNO, William F. CANNON, and Pau O’SULLIVAN**

*Geologic implications of detrital zircon U-Pb ages from Archean and Paleoproterozoic strata in central Minnesota and the Gogebic Range of Wisconsin and Michigan, USA*

**3:20 R. SALERNO, W.F. CANNON, A. SOUDERS, J.M. THOMPSON, and J. VERVOORT**

*Constraining the timing of crustal exhumation following the Penokean orogeny using U-Pb, Sm-Nd, and Lu-Hf geochronology and microstructural analysis*

**3:40 James DeGRAFF, Chad DEERING, and James JONES III**

*The Archean Carney Lake gneiss complex in Michigan’s Upper Peninsula: Preliminary subdivisions with age constraints*

**4:00 \*Omar Khalil DROUBI, Erik SCHOONOVER, Mona-Liza SIRBESCU, Joshua GARBER, and Chlo BONAMICI**

*Geochronology of lithium mineralization in the Florence pegmatite field, WI, USA*

**4:20              END OF TECHNICAL SESSION IV**

## **Thursday evening May 15, 2024**

**5:30 pm**      **RECEPTION AND CASH BAR** (Mountain Iron Convention Center)

**6:30 pm**      **ANNUAL BANQUET** (Mountain Iron Convention Center)

**2025 Goldich Medal Recipient:** Robert Michael Easton

**Banquet Speaker:** Pete Kero, Mine to Mountain Bike Mecca:

The story of the Redhead Mountain Bike Park

## **Friday - May 16, 2025**

**8:15 INTRODUCTORY REMARKS AND UPDATES** (Mountain Iron Community Center)

*Amy Radakovich, Allison Severson, Eric Nowariak, Stacy Saari, Aaron C. Hirsch; Co-Chairs, 2025 ILSG*

## **TECHNICAL SESSION V – ORAL PRESENTATIONS**

*Session Chair: Aaron Hirsch*

**8:20 Wouter BLEEKER, Michael HAMILTON, and Sandra KAMO**

*Paleoproterozoic mantle plume tracks shaping the southern margin of the Superior craton and the geology of the Lake Superior region*

**8:40 Max ROHRMAN**

*Plume control on the initiation of Mid-Continent Rift breakup using Unconformities: Implications for the Tectono-magmatic evolution and mineral deposits*

**9:00 James TOLLEY, Pete HOLLINGS, Kevin MEXIA DURAN, and Myles HARDING**

*Evaluating Ni in Olivine as a Prospectivity Indicator for Magmatic Ni-Cu-(PGE) Deposits: A Preliminary Study from the Midcontinent Rift System.*

**9:20 James TOLLEY, Jacob HANLEY, James CROWLEY, Sasha TSAY, Zoltan ZAJACZ, and Pete HOLLINGS**

*A Porphyry in a Rift? Constraining the Petrogenesis of the Jogan Porphyry, Mamainse Point, Ontario, Canada: Insights from Zircon and Melt Inclusion Geochemistry*

**9:40 Nicholas SWANSON-HYSELL, Eben B. HODGIN, Tadesse ALEMU, Anthony FUENTES, Yiming ZHANG, Sarah SLOTZNICK, and Luke FAIRCHILD**

*Midcontinent Rift extension ceased and the rift inverted due to the Grenvillian orogeny*

**10:00**      **END OF TECHNICAL SESSION V**

**10:00-10:20 COFFEE BREAK** – Sponsored by MRGS

## **TECHNICAL SESSION VI – POSTER PRESENTATIONS**

*Session Chair: Robert Lodge*

**10:00-11:30 AUTHORS PRESENT AT THEIR POSTERS**

**11:30 END OF TECHNICAL SESSION VI**

**11:30-1:00 LUNCH BREAK**

- Buffet lunch provided-

## **TECHNICAL SESSION VII – ORAL PRESENTATIONS**

*Session Chair: Eric Nowariak*

**1:00 Steven D.J. BAUMANN**

*Pembine-Wausau Terrane as an Icelandic style island overthrust onto Archean basement, instead of an island arc or continental fragment accretion*

**1:20 Jiří ŽÁK, Filip TOMEK, Václav KACHLÍK, František VACEK, Martin SVOJTKA, and Lukáš ACKERMAN**

*Broadly coeval but migrating deformation, plutonism and deposition in the northeastern Superior Province, Québec: evidence of hot accretionary orogeny and oroclinal folding in the late Archean?*

**1:40 Mark SMYK, Pete HOLLINGS, Riku METSARANTA, Robert CUNDARI, Stephen KISSIN, and Colleen KURCINKA**

*Basaltic rocks of the Animikie Group in Ontario: Geochemical characteristics and tectonic significance*

**2:00 W. F. CANNON, M. Rebecca STOKES, Ross A. SALERNO**

*Micromineralogy and textures in the Sudbury impact layer on the Mesabi Iron Range, Minnesota: record of processes in the proximal-distal ejecta transition zone*

**2:20 END OF TECHNICAL SESSION VII**

**2:20 COFFEE BREAK**

## TECHNICAL SESSION VIII – ORAL PRESENTATIONS

*Session Chair: Amy Radakovich*

**2:40 J.D. VERHOEVEN and Tim ZOWADA**

*Origin of magnetic black sand found on the south Shore of Lake Superior*

**3:00 Erika VYE and Daniel LIZZADRO-MCPHERSON**

*Geospatial Learning Resources to Explore Relationships with Keweenaw Geology*

**3:20 Allan MACTAVISH, Peter HINZ, +George HUDAK, Phil LARSON, Allan AUBUT, Terry BOERBOOM, Vern CHILTON, Jim DeGRAFF, Tom ERICKSON, Barb FAULKNER, Isabel SERRANO, Larry and ZANKO**

*An informal review of the ILSG field trip to Hawaii: January and February 2025*

**4:00 END OF TECHNICAL SESSION VIII**

**4:00 Presentation of Student Awards**

*Best Student Paper Awards – Student award committee*

*Student Travel/Participation Awards – Amy Radakovich*

*MRGS Awards – Mark Severson*

**4:30 Concluding Remarks and Field Trips**

*Amy Radakovich, Allison Severson, Eric Nowariak, Stacy Saari, Aaron C. Hirsch; Co-Chairs, 2025 ILSG*

**END OF TECHNICAL SESSIONS OF THE 71st ANNUAL MEETING**

## **Saturday May 17, 2025**

Field trips begin and end at the Mountain Iron Community Center

### **8:00 am – 5:00 pm POST-MEETING FIELD TRIPS**

#### **Trip 5: Neoarchean alkaline intrusions in the Wawa and Quetico subprovinces**

Terry Boerboom (Minnesota Geological Survey, retired); Amy Radakovich (Minnesota Geological Survey)

#### **Trip 6: Unique Keweenaw inclusion (Colvin Creek) in the Duluth Complex**

Mark Severson (Natural Resources Research Institute, Teck, retired); Allison Severson (Minnesota Geological Survey); Lauri Severson (Earth Science teacher, retired)

#### **Trip 7: Classic outcrops of Northeastern Minnesota**

Dean M. Peterson (Big Rock Exploration); George J. Hudak (University of Minnesota, George Hudak Geosciences P.L.L.C.)

#### **Trip 8: Glacial Lake Norwood and the Koochiching Lobe**

Phillip Larson (Vesterheim Geoscience PLC); Andrew Breckinridge (University of Wisconsin-Superior); Howard Mooers (University of Minnesota, Duluth)

## POSTER PRESENTATIONS

\* Denotes a student eligible for Best Student Paper Award. To be eligible students must have graduated no more than one month before the ILSG meeting, be first author, and present the paper at the meeting

+ Denotes author that will present the paper if different than the first author.

**Numbered Posters and Abstracts are in sequential order**

1. **\*Zsuzsanna ALLERTON, George HUDAK, Guy EVANS, Xinyuan ZHENG, and Christian TEYSSIER**

*Geochemical analyses of banded iron formations and formerly mined iron ore in the Lake Vermilion-Soudan Underground Mine State Park, NE Minnesota*

2. **\*Madelyn BANKS, Latisha BRENGMAN, Athena EYSTER**

*Linking whole rock geochemical data with micro-scale mineral characterization of oxidation reactions in the Biwabik Iron Formation, MN, USA*

3. **Howard MOOERS, Mark SEVERSON, Peter JONGEWAARD, and Phillip LARSON**

*US Steel Corporation / Ralph W. Marsden iron ore collection*

4. **\*Sarah JAROZEWSKI, Paige DUFFY, Cole BARRÉ, Latisha BRENGMAN, and Athena EYSTER**

*Mapping oxidation reactions in iron-rich rocks from northeast Minnesota, USA.*

5. **\*Celia L. CORTOPASSI, Zsuzsanna P. ALLERTON, Joshua M. FEINBERG**

*Alteration of magnetic mineralogy in the Giants Range Batholith by the Duluth Complex*

6. **\*Samara GRIES, Robert W.D. LODGE, Sara HANEL, and Robert HOOPER**

*Rare-element Geochemistry of the Eau Claire River Complex Pegmatites*

7. **\*Linsey HULA and Dyanna CZECK**

*Emplacement of the Mesoproterozoic Wausau Syenite Complex, Wisconsin*

8. **\*Renee O. JEUTTER and Robert W.D. LODGE**

*Geology and Geochemistry of the Mesoproterozoic Round Lake Intrusion and associated Ti-Mineralization, Northern Wisconsin*

9. **\*Bekah R. THOMPSON and Robert W.D. LODGE**

*Ni-Cu-PGE Mineralization at the Mineral Lake Intrusive Complex, northern Wisconsin*

10. **\*Lyndsie A. VICKERS and Robert W.D. LODGE**

*Zircon Petrochronology of the Eau Claire Volcanic Complex in the Marshfield Terrane of the Penokean Orogen, Northcentral Wisconsin*

11. **\*Andrew A. CASPER and Robert W.D. LODGE**

*R Geology and Mineralization of the Plover Au Prospect, Marathon County, Wisconsin*

- 12. William FITZPATRICK**  
*Textural and chemical analysis of sphalerite ores from the Highland Subdistrict, Upper Mississippi Valley Zinc-Lead District, Wisconsin*
- 13. \*Haley P. JOHANNESSEN and Robert W.D. LODGE**  
*Geology and Geochemistry of the Ritche Creek Cu-Zn deposit, North central Wisconsin*
- 14. \*Aidan O. KWIATKOWSKI and Robert W.D. LODGE**  
*Zircon Petrochronology of Wisconsin's Volcanogenic Massive Sulfide Deposits, Northcentral Wisconsin*
- 15. Sara PEARSON, Nolan GAMET, Molly SHALIFOE, Ashley QUIGLEY, and Robert MAHIN**  
*Michigan Geological Survey's Contributions to the USGS Earth MRI National Mine Waste Inventory Effort*
- 16. Ashley K. QUIGLEY, Robert A. MAHIN, and Nolan G. GAMET**  
*Critical Mineral Potential of the Northern Margin of the Watersmeet Gneiss Dome, MI USA*
- 17. \*MaryElizabeth SHALIFOE and Peter VOICE**  
*Identifying Abandoned Mine Surficial Features Using Mask R-CNN, Upper Peninsula Michigan.*
- 18. Sophie CHURCHLEY and Philip FRALICK**  
*Unusual early diagenetic structures in the Paleoproterozoic Gunflint Formation, Ontario, Canada*
- 19. Gordon MEDARIS Jr. and Dave MALONE**  
*Post-Penokean and Pre-Yavapai Magmatism and Sedimentation in Central Wisconsin (Southern Lake Superior Region)*
- 20. Esther K. STEWART, Michael TAPPA, Ann BAUER, Latisha BRENGMAN, and Anthony PRAVE**  
*Sedimentologic and geochemical evidence of marine incursion to the Oronto Group basin, southern Lake Superior region, at ca. 1.08 Ga*
- 21. Carsyn AMES and Brad GOTTSCHALK**  
*High resolution thin-section scanning and metadata capture- WGNHS Data Preservation Project 2024 early efforts*
- 22. Nate DANIELS, Grace MCELLISTREM, Raeann VOGEL, and Michael BRAUNAGEL**  
*Architecture of the Douglas Fault damage zone, northwest Wisconsin*
- 23. Mark B. LONGACRE and William J. HINZE, William**  
*Geologic Interpretation of Filtered Gravity and Magnetic Anomalies of the Baraboo Range*
- 24. Jack MALONE, David MALONE, Raymond ANDERSON, Ryan CLARK**  
*Refining the Age and Occurrence of Basement Rocks in Northwest Iowa: Implications for Precambrian Tectonics and Magmatic Evolution of the Laurentian Midcontinent*

# ABSTRACTS

**Geochemical analyses of banded iron formations and formerly mined iron ore in the Lake Vermilion-Soudan Underground Mine State Park, NE Minnesota**  
**ALLERTON, Zsuzsanna<sup>1</sup>, HUDAK, George<sup>1,2,3</sup>, EVANS, Guy<sup>1</sup>, ZHENG, Xinyuan<sup>1</sup>, and TEYSSIER, Christian<sup>1</sup>**

<sup>1</sup>*Earth & Environmental Sciences, University of Minnesota, Minneapolis, MN 55455, USA*

<sup>2</sup>*Earth and Environmental Sciences, University of Minnesota, Duluth, MN 55812, USA*

<sup>3</sup>*George Hudak Geosciences P.L.L.C., Duluth, MN 55804, USA*

The Lake Vermilion-Soudan Underground Mine State Park in northeastern Minnesota is known for its underground tours in the former iron mine that was operational between 1884-1962 (Klinger, 1960). The mine contains lenticular-shaped ore bodies enclosed in variably altered banded iron formations (BIFs) that were upgraded to massive hematite iron ore during replacement-style hydrothermal alteration (Gruner, 1926; Klinger, 1960; Thompson, 2015). The timing of ore mineralization is constrained to 1.8-1.6 Ga (Allerton, 2024b). The widely accepted simplified genetic model for these ore deposits involves hydrothermal fluids that leached silica from BIFs and concentrated iron as hematite. Here we utilize historic and recently acquired whole rock major, trace and rare earth element lithogeochemical analyses to perform mass balance evaluations via the isocon method (Grant, 2005) and iron stable isotope geochemistry to propose a new hydrothermal model to better constrain the transition from BIF to iron ore.

Eight BIF and twelve ore samples from Thompson (2015) were utilized for this study. BIFs show varying degrees of alteration adjacent to the orebodies, whereas iron ore samples comprise massive hematite  $\pm$  chlorite. Our data include eight additional samples; four least altered and two hematite-altered BIFs collected from surface outcrops, and two iron ore samples that are 1) high-grade hematite ore with primary phase microcrystalline hematite-martite (MCH-MT) with minimal chlorite and 2) lower grade ore with abundant secondary quartz and microplaty hematite (MPH; Allerton, 2024b). The Fe isotope analysis incorporates variably deformed gabbroic rocks and chlorite schist adjacent to the ore bodies as well.

Lithogeochemical analyses of 14 BIFs and 14 iron ore samples indicate inverse correlation between  $\text{SiO}_2$  and  $\text{Fe}_2\text{O}_{3(\text{total})}$ ; BIF has high  $\text{SiO}_2$  and low  $\text{Fe}_2\text{O}_{3(\text{total})}$  contents, whereas iron ore displays low in  $\text{SiO}_2$  and  $\text{Fe}_2\text{O}_{3(\text{total})}$ . Statistical evaluations suggest that high strength field elements (HFSE) are immobile and therefore have been selected for isocon analysis. Utilizing a HFSE ‘best fit’ isocon, the system shows almost complete  $\text{SiO}_2$ -loss (99%) and 54%  $\text{Fe}_2\text{O}_3$ -loss from least altered BIF to high-grade ore (Fig. 1A), suggesting that greater loss of silica relative to iron has resulted in a net concentration of iron. Moreover, there is secondary quartz and MPH in the lower grade ore based on petrography, indicating the lower-grade ore postdates the high-grade ore. Isocon analysis shows  $\text{SiO}_2$ -gain and continued  $\text{Fe}_3\text{O}_2$ -loss from high-grade to lower grade ore (Fig. 1B). The Fe stable isotope results attest to this by presenting higher  $\delta^{56}\text{Fe}$  values for BIFs that decrease from less to more altered BIF. MCH-MT in high-grade ore displays even lower  $\delta^{56}\text{Fe}$  values, and chlorite within fractures of high-grade ore shows similar values to secondary quartz and MPH in heterogeneous ore, suggestive of paragenesis of two different hematite phases and gangue minerals (Fig. 2).

Our new hydrothermal model proposes continuous removal of Fe, entailing coeval Si mobilization and removal from BIF to high-grade MCH-MT ore and re-deposition into lower grade MPH ore. These hypotheses are supported by detailed analyses of lithogeochemistry, mineral textures, and Fe stable isotopes.

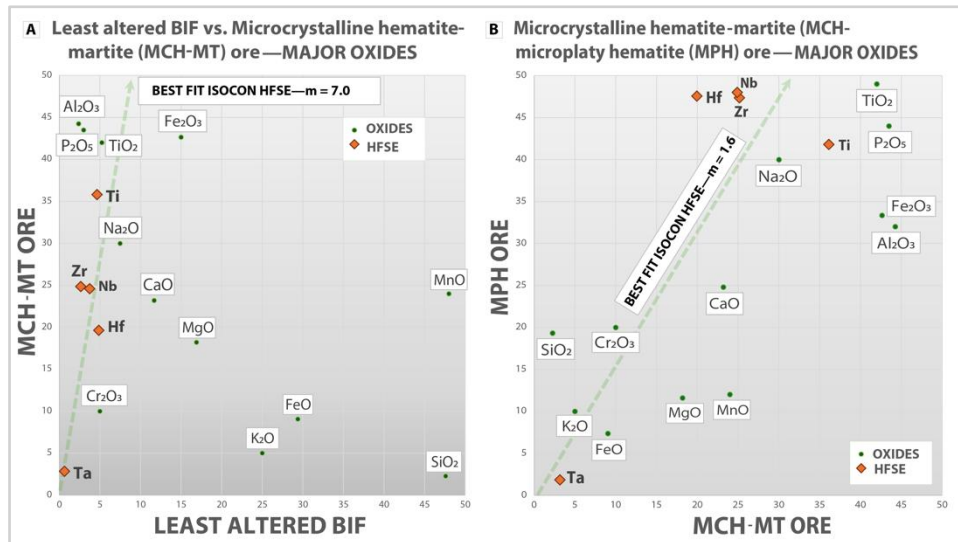


Figure 1: A) Diagram displays major oxides of least altered BIF (x-axis) against MCH-MT ore (y-axis) and B) MCH-MT ore (x-axis) against MPH ore (y-axis). Ratios show gains and losses are calculated based on the slope of HFSE best fit isocons.

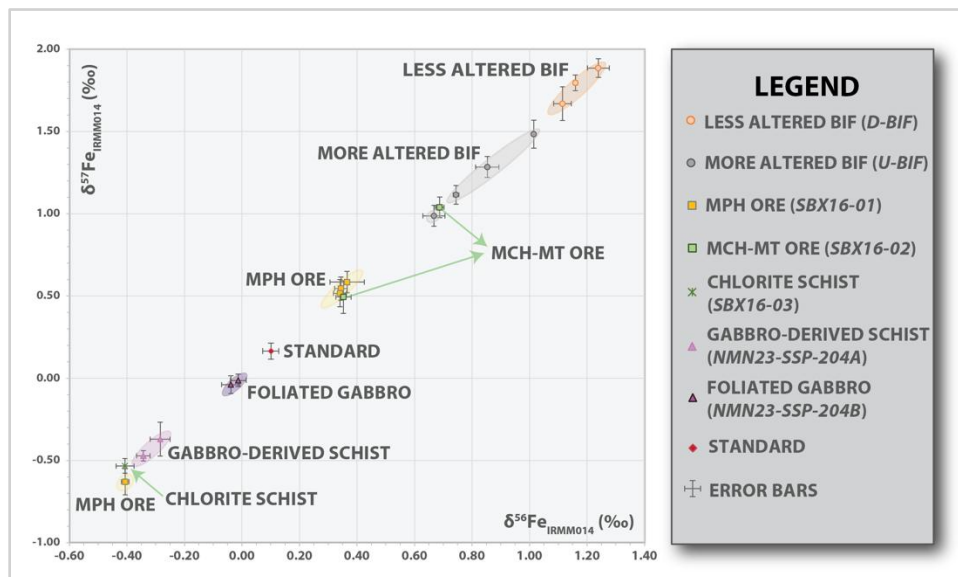


Figure 2: Diagram shows decreasing  $\delta^{57}\text{Fe}/\delta^{56}\text{Fe}$  values of less and more BIFs, MCH-MT and MPH ore samples, and lithologies adjacent to the ore bodies in Sudan; foliated gabbro, gabbro-derived schist, chlorite schist. Values are calibrated to BHVO-2 iron standard commonly used in Fe stable isotone geochemistry.

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- Klinger, F.L., 1960. Geology and ore deposits of the Soudan mine, St. Louis County, Minnesota [thesis].
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## High resolution thin-section scanning and metadata capture- WGNHS Data Preservation Project 2024 early efforts

AMES, Carsyn<sup>1</sup> and GOTTSCHALK, Brad<sup>1</sup>

<sup>1</sup>*Wisconsin Geological and Natural History Survey, UW-Madison, 3817 Mineral Point Rd, Madison, WI 53704 USA*

The Wisconsin Geological and Natural History Survey (WGNHS) has recently undertaken an effort to scan approximately 3800 of the 4800 historical thin sections held in WGNHS collections as part of the USGS-National Geological and Geophysical Data Preservation Program (NGGDPP). This work builds upon a number of previous projects including: a 2011 NGGDPP project to inventory all thin sections in the WGNHS collections, an internal project to catalog fields notebooks and refine locations of recorded samples, a pilot study to develop a workflow for scanning and editing high resolution photos of thin sections, and a project to inventory and collect metadata from an extensive collection of samples donated to WGNHS by Gene LaBerge (UW-Oshkosh). Building on the lessons learned from these prior studies and methods outlined in Leung and McDonald (2023), we have developed a workflow to scan thin sections using a Plustek OpticFilm 8200i film scanner (Figures 1a and 1c) and SilverFastSE Plus software with settings shown in Figure 1b. Forty-eight-bit raw images are produced in both plane, non-polarized light and cross-polarized light (Figure 2). Images are edited post scanning in Adobe Lightroom to enhance the sharpness and exposure to better replicate what users see when viewing thin sections with a petrographic microscope. Scanning and editing images takes approximately 10 minutes per thin section. Photos are stored in TIFF format and are intended to be served on the WGNHS Dataviewer for public access.

Thin sections included in this project capture a wide range of lithologies from several Wisconsin counties. Many samples represent some of the first efforts to survey the natural resources and map the geology of northern Wisconsin. The original data associated with the thin sections is archived in historic field notebooks archived at the WGNHS and includes documentation of geomorphology, bedrock and glacial geology, and magnetic susceptibilities of encountered bedrock units. Locations are recorded in Public Land Survey System (PLSS) notation. Samples with at least section level location information were included in this project; many of the locations given in the field notes can be narrowed down to quarter-section designation with certainty. In the initial phase of this ongoing project we have focused on scanning and entering metadata for samples in and around Florence County, Wisconsin. Precambrian iron formation in this area was mined from 1880-1931 to produce some three million tons of hematite and limonite ore (Brown B., 2021). This project has focused on capturing lithological information from samples in this area, which is characterized by complex Precambrian stratigraphy and structure. Upon project completion, high resolution thin section images will be made publicly available online using the WGNHS Dataviewer. Additionally, all metadata will be uploaded to the USGS's ReSciColl collection and the WGNHS internal database (Geobase).



Figure 1: A) Plustek Optic Film 8200i scanner and accompanying film tray. B) Scanner settings to be used during the proposed project. Note the 600 ppi preset and further 7,200 ppi adjustable resolution. Thin sections are scanned in 48-bit HDR Raw C) Tray with card stock paper cut to better hold thin sections. Note the two slots on the right are fitted with linear polarizing screens that sandwich the thin sections. The polarized screens are oriented to cross polarize the light when scanning.

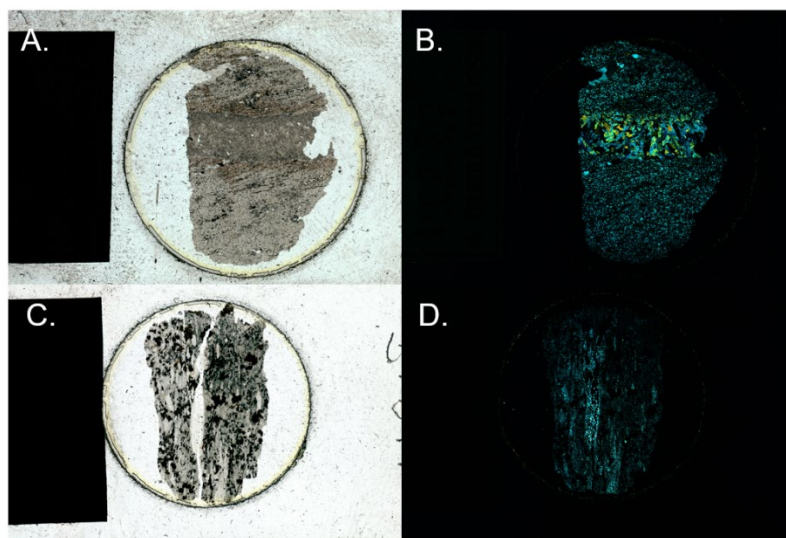


Figure 2: High resolution thin section images scanned as part of the pilot project. A. and C. were scanned using plane, non-polarized light; B. and D. were scanned using cross polarized light.

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- Leung, D. D.V., and McDonald, A.M., 2023. Picture-perfect petrography: affordable thin-section scanning for geoscientists in the digital era. *The Canadian Journal of Mineralogy and Petrology*, 61: 1045-1050.

## **A Contrarian View: Thoughts on the Genesis of the Tamarack Ni-Cu Deposit.**

**AUBUT, Alan<sup>1</sup>**

*<sup>1</sup>Sibley Basin Group Ltd., PO Box 304, Nipigon, ON P0T 2J0 Canada*

The Tamarack Ni-Cu deposit has been attributed as being of intrusive origin (Goldner, 2021; Taranovic et al., 2018). There are many nickel deposits hosted by ultramafic bodies that display clear evidence of being the product of extrusive flows, often exhibiting the same key features used to invoke an intrusive origin (e.g. Arndt, 1975; Hill et al., 1995; Hubbert and Sparks, 1985; Marston et al., 1981).

This includes the nickel deposits of the Kambalda district of Australia, Pechenga in the Kola Peninsula of western Russia, Raglan in northern Quebec and Thompson in northern Manitoba. All have been, or currently are, attributed to the intrusion of ultramafic sills (e.g. Bleeker, 1990; Marston et al., 1981; Melezhik et al., 1994). Key evidence in support of this model is that the ultramafic bodies typically exhibit at least some differentiation and are sub-concordant to the host sediments. This tendency to default to an intrusion model now includes the Tamarack deposit in Minnesota even though an extrusion model is more valid.

The major komatiite hosted nickel deposits listed above share common features: 1) the nickel mineralisation is hosted by ultramafic rocks; 2) the sulphides are at the stratigraphic base of the host ultramafics; 3) the ultramafic rocks are hosted by, or in contact with, sulphidic and carbonaceous argillaceous rocks; 4) the ultramafic bodies are stratabound and generally conformable to the host lithology; and 5) they are hosted within extensional basins usually with a significant sedimentary component with Kambalda being the one exception.

But there is a density “problem” in that ultramafic magmas are typically denser than the host rocks, especially when they are sedimentary. When rocks melt, they become about 10% less dense. In the case of ultramafic rocks, the average density is about 3.0 g/cc (Nisbet et al., 1993) while the crust has a density of 2.7 g/cc or less. To move upward from the mantle through the crust there must have been a mechanism other than buoyancy.

“Overpressure” is a valid explanation (Sleep, 1974, 1992). Magma plumes in a mantle plume move upward due to buoyancy to the Mantle-Crust boundary. There it collects and then moves laterally thus creating extensional forces in the overlying crust. This accumulating magma would be constrained by the overlying lithostatic load and in doing so would build up overpressure. If the crust thins enough vertical fractures can form allowing the trapped magma to escape due to the built-up overpressure exceeding the lithostatic load. At surface the hot, dense ultramafic magma would then flow over, and into, deep water sediments where the magma would mechanically and thermally erode and assimilate sulphide rich sediments.

Tamarack shows all the same characteristics as other Ni-Cu deposits associated with rift basins and features that are more easily explained by extrusive flow of komatiitic magma. As such the intrusive emplacement model currently favoured should be reviewed and serious consideration given to emplacement by extrusion of a high-density magma driven by overpressure.

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## **An overview of the geology, tectonic setting, and occurrence of sulphide mineralization in the Lac Des Iles Intrusive Suite**

**BAIN, Wyatt<sup>1</sup>, TOLLEY, James <sup>2</sup>, and HOLLINGS, Peter <sup>2</sup>**

<sup>1</sup>*Department of Earth Sciences, Western University, 1151 Richmond St, London, ON N6A 5B7 Canada*

<sup>2</sup>*Department of Geology, Lakehead University, 955 Oliver Road Thunder Bay, ON P7B 5E1 Canada*

The Lac des Iles (LDI) mafic-ultramafic complex hosts a world-class platinum group element (PGE) deposit and is spatially associated with a suite of mafic-ultramafic satellite intrusions (i.e. the LDI-intrusive suite; LDI-IS). The intrusions are hosted in the crystalline rocks of the Wabigoon subprovince, along its eastern contact with the sedimentary and volcanic rocks of the Quetico subprovince. Previous work identified textural and geochemical similarities between the LDI-IS and the mineralized rocks of the LDI complex that likely reflect a temporal and genetic association, and perhaps a similar degree of prospectivity for PGE mineralization (Stone et al., 2003). Here, we present an overview of the geology and setting of the LDI-IS, as well as new geochronology, isotopic data, and parental melt modelling.

The LDI-IS (Tib Lake, Legris Lake, Wakino Lake, Demars Lake, Dog River, Taman Lake, and Buck Lake; Fig. 1a) are mostly leucogabbro to gabbro in composition but commonly include hornblende gabbro, hornblende, and minor peridotite and pyroxenite. Zircon U-Pb ages for mineralized gabbro from the Buck Lake ( $2698.1 \pm 1.6$  Ma), Wakino Lake ( $2696.6 \pm 0.8$  Ma), Demars Lake ( $2694.1 \pm 1.5$  Ma), Legris Lake ( $2690.6 \pm 0.8$  Ma), Dog River ( $2689.9 \pm 0.7$  Ma), and Tib Lake ( $2685.9 \pm 1.6$  Ma) intrusions show a spatial trend of younging to the north and demonstrate a temporal association with the Lac des Iles Mine Block intrusion ( $2689.0 \pm 1.0$  Ma; Stone, 2010; Fig 1 b).

Trace element profiles for modelled parental melts are similar across most of the LDI-IS and are consistent with an arc setting and a common parental magma source reservoir. However, modelled REE profiles for some cyclic units in the Tib lake intrusion were more evolved and enriched in light rare earth elements. Similar patterns are reported in modelled parental melts from North LDI and are consistent with mixing between primitive and more evolved, siliceous magmas (Djon et al., 2017). Though magma mixing influenced the geochemical evolution of the Tib lake intrusion, cyclic units with more evolved signatures were not significantly mineralized.

Whole rock  $\epsilon_{\text{NdT}}$  values of gabbroic rocks from the LDI-IS and the Lac des Iles complex overlap with the tonalitic rocks of the Wabigoon subprovince in older intrusions and trend toward increasingly negative values in younger intrusions (Fig. 1c). This suggests assimilation of Wabigoon tonalite by LDI-IS parental magmas early in the formation of this magmatic system, and greater degrees of contamination by Quetico metasediment over time.

Magmatic sulphides from the Legris Lake intrusion have  $\delta^{34}\text{S}$  values that overlap the mantle range but trend toward the composition of Wabigoon tonalite (Bain et al., 2023). This suggests that external S or Si addition from the tantalite drove sulphide saturation during its formation. However, a comparison of whole rock S/Se and Cu/Pd ratios of mineralized lithologies across the LDI-IS suggest that sulphide melt retention during emplacement was a more crucial control on the occurrence of PGE-bearing sulphide mineralization than the source of S or the timing of sulphide saturation.

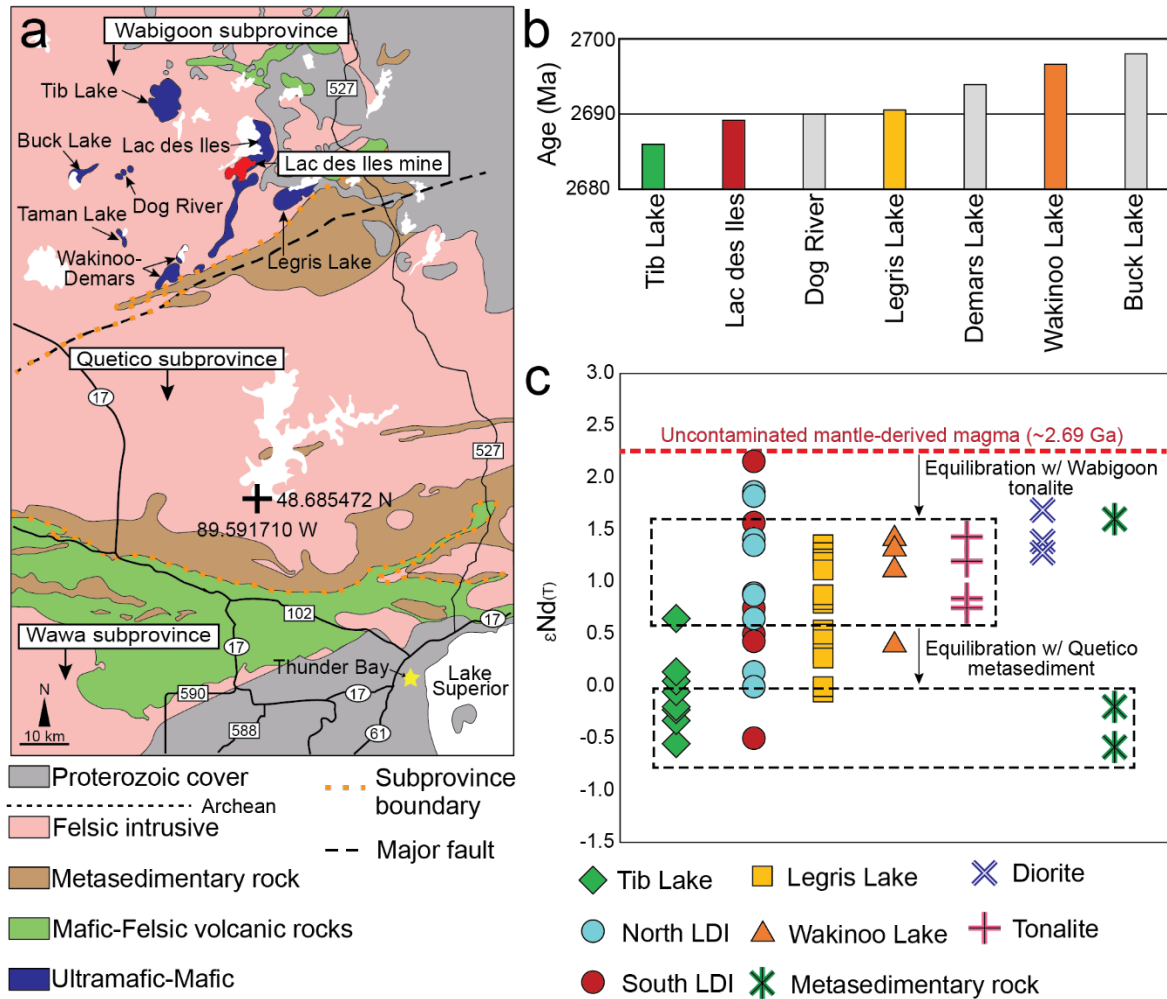


Figure 1: **a.** Regional geologic map showing locations of Thunder Bay, the Lac des Iles mine (in red), and the Lac des Iles intrusive suite (in blue). **b.** U-Pb ages for individual intrusions in the Lac des Iles intrusive suite. **c.** Whole-rock  $\epsilon_{Nd}(t)$  values for the LDI intrusive suite and host rock lithologies. North LDI and South LDI data from Brüggmann et al. 1997

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## Linking whole rock geochemical data with micro-scale mineral characterization of oxidation reactions in the Biwabik Iron Formation, MN, USA

BANKS, Madelyn<sup>1</sup>, BRENGMAN, Latisha<sup>1</sup>, EYSTER, Athena<sup>2</sup>

<sup>1</sup>*Department of Earth and Environmental Sciences, University of Minnesota Duluth, Heller Hall, 1114 Kirby Drive, Duluth, MN 55812, USA*

<sup>2</sup>*Department of Earth and Climate Sciences, Tufts University, Lane Hall, 2 North Hill Road, Medford, MA 02155, USA*

Oxidation and hydration reactions in iron-rich chemical sedimentary rocks are of critical interest because they signify post-depositional changes often linked to later weathering and fluid alteration. Evaluating oxidation and hydration reactions present in iron formations is therefore required to separate out depositional signals in mineralogical and geochemical data from those that link to post-depositional mineral reactions and enrichment processes (Geymond et al., 2022). The Biwabik iron formation is a part of a well-preserved, sub-greenschist lithologic assemblage containing three major meta-sedimentary formations known together as the Animike Group (e.g. Severson, 2009 and references therein). Previous work (e.g. Duncanson et al., 2024 and references therein) demonstrated the preservation of numerous mineral reactions in the Biwabik iron formation, making it an ideal location to test how mineral reactions link directly to whole rock geochemical signals. To evaluate the relative timing of different oxidation and hydration reactions and how they link to whole rock geochemical data, we integrate core, petrographic, and scanning electron microscope observations with whole rock digestion ICP-MS geochemical datasets from core LWD-99-01 (n = 60) of the Biwabik iron formation.

Two key oxidation reactions identified in this work include (1) magnetite to hematite and (2) carbonate to magnetite. Mineral reactions are documented by cross-cutting relationships (Figure 1A-D). The mineral reaction of magnetite to hematite (possibly via the recrystallization of metastable maghemite,  $2(\alpha\text{Fe}_3\text{O}_4) + \text{H}_2\text{O} \leftrightarrow 3(\gamma\text{Fe}_2\text{O}_3) + \text{H}_2$ ; Geymond et al., 2023) is present in all four informal lithologic subunits of the Biwabik iron formation, occurring in 48% (n = 23) of samples (n = 48) across these units. The mineral reaction of carbonate to magnetite ( $3\text{FeCO}_3 + \text{H}_2\text{O} \rightarrow \text{Fe}_3\text{O}_4 + 3\text{CO}_2 + \text{H}_2$ , Duncanson et al., 2024) is also present in all four informal lithologic subunits of the Biwabik Iron Formation, occurring in 77% (n = 37) of samples (n = 48) across these units. Based on 64 EDS point analyses of 4 representative samples from each subunit of the Biwabik iron formation, dominant carbonate minerals range from siderite at the base of the stratigraphy, to ankerite, dolomite, and calcite towards the top.

Combined, carbonate compositional variability and zonation indicate element exchange during multiple generations of post-depositional fluid alteration, and cross-cutting relationships between carbonate-magnetite, and magnetite-hematite indicate post-depositional oxidation via fluid interaction with pre-existing reduced iron phases. Dissolution of carbonate may have created porosity providing pathways for oxidizing fluids, and further oxidation. Despite these later oxidation reactions, whole rock geochemical data preserves lithology specific signals of oxic vs. anoxic conditions, independent of the presence of the post-formational reactions outlined above. Lower stratigraphic units preserve oxic signals even with ferrous iron phases like siderite and greenalite preserved, while upper stratigraphic units preserve anoxic signals, despite the presence of hematite. Overall, bulk geochemical data from lithologic subunits of the Biwabik Iron Formation do not preserve clear signals associated with post-depositional mineral assemblage modification and oxidation documented by detailed petrographic work.

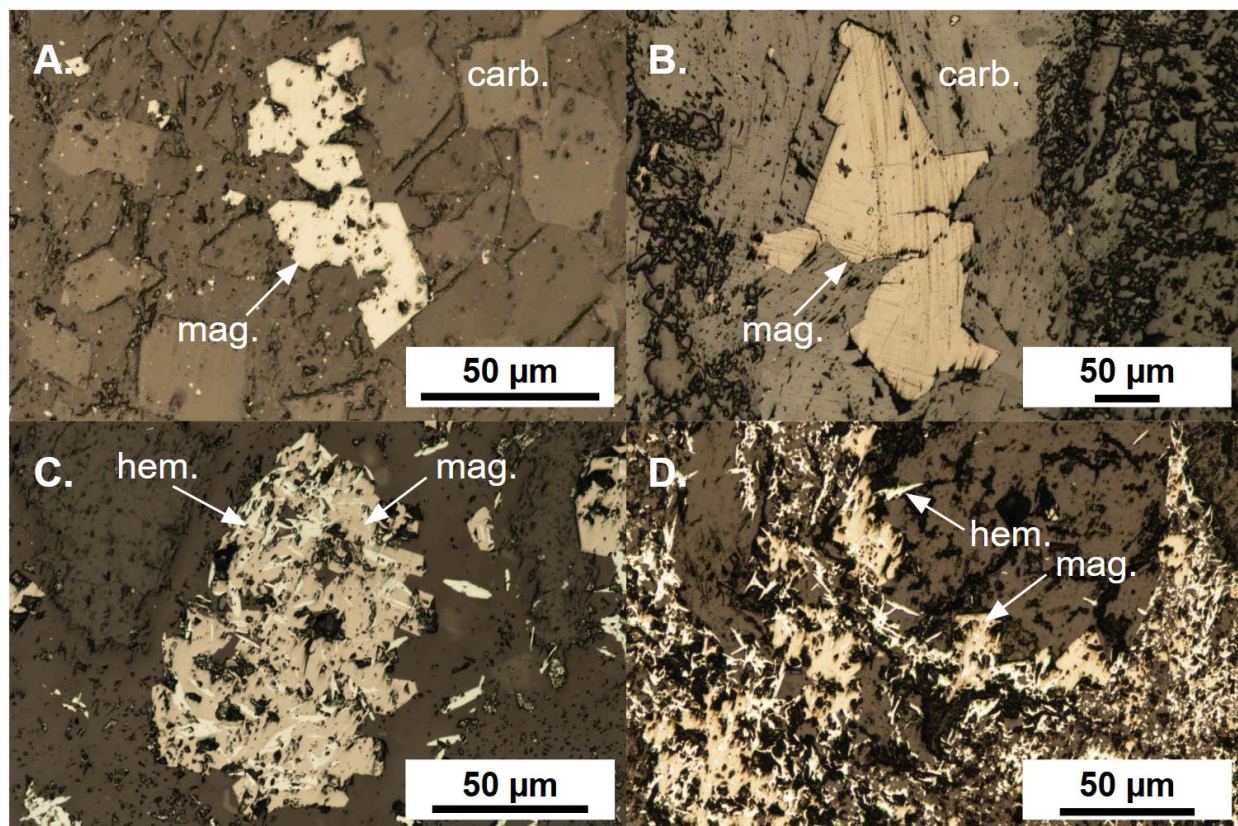


Figure 1: *LWD-99-01 reflected light photomicrographs documenting cross-cutting relationships between mineral phases. A. Upper Slaty sample MIR-17-15 carbonate granule cross-cut by euhedral magnetite (mag) in 20x. B. Lower Cherty sample MIR-19-14 carbonate granule (carb) cross-cut by euhedral magnetite (mag) in 5x. C. Upper Cherty sample MIR-19-15 magnetite crystal (mag) cross-cut by platy hematite (hem) in 20x. D. Lower Slaty sample U-05 magnetite crystals (mag) crosscut by platy hematite (hem) at the edge of a silicate granule in 10x.*

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## **Pembin-Wausau Terrane as an Icelandic style island overthrust onto Archean basement, instead of an island arc or continental fragment accretion**

**BAUMANN, Steven D.J.**

*Midwest Institute of Geosciences and Engineering*

Since at least the 1960s, we have thought of the Pembine-Wausau Terrane (PWT) as an island arc or continental fragment accretion, smashed between the Superior Craton to the north and the Marshfield Terrane to the south. We all have seen a fault zone appear on geologic maps of the border between the Upper Peninsula of Michigan and northeast Wisconsin called the Niagara Fault Zone (NFZ). There is only one major problem, no one has ever found the NFZ. It doesn't outcrop anywhere, it does not appear in well records, nor clearly on gravity maps, or magnetic maps. Often where it is inferred it can be interpreted other ways. And the NFZ isn't reflected in any smaller chronostratigraphically equivalent structures that do outcrop.

I have found white unbaked quartzite pebbles (the Sturgeon Quartzite) north of the NFZ (fig. 1). The host rock of these pebbles according to maps, are metamorphic rocks that supposedly have an igneous protolith. I find that very hard to reconcile with present modeling. As I have looked at the highly deformed rocks of the Florence Wisconsin, Iron Mountain Michigan, and Norway Michigan areas, I have come to the conclusion that many rocks mapped as metaigneous, are in fact, metasedimentary. I have been working on a local cross section for several years with my observations. I am coming to the conclusion that the mafic rocks and metasediments to the north of where the NFZ has traditionally been mapped, are more or less continuous and correlative to the mafic and metasedimentary rocks to the south of it. Interpretation of the rocks is understandably very difficult as the rocks are highly metamorphosed and deformed.

This work is preliminary. My interpretations could change. But this is where the evidence is leading me thus far. So, if the area that is mapped as the NFZ is not a fault zone, what is it? I see it as one of two possibilities. It could be more of a shear zone formed from a more lateral accretion of a volcanically active, partially rifted Archean sliver, similar in appearance to Baja California. Shearing would be hard to see expressed in the rocks, just as it is for other covered shear zones further north. The second possibility is that the PWT was originally an Icelandic style island on a spreading center that would eventually become subducted under the Superior Craton, similar to the East Pacific Rise, before subduction switched to the south as the Marshfield Terrane approached. Its suspected Archean basement could be explained by a thin skinned over thrusting of the PWT over a small sliver of Archean crust, while volcanism was ongoing. The age of the xenocryst zircons expected to be Archean are only  $2,607 \pm 22$  Ma (VanWyck and Johnson. 1997). This is similar to many Archean ages of the Superior Craton. It is still a possibility the Penokean was a continental fragment like the Marshfield Terrane, only far more incomplete and still covered with younger deposits, but this cannot be the default without understand the nature of the NFZ, if it even exists. The Archean basement of the PWT could also be some sort of an extension of nearly in situ Superior Craton, that hosted the PWT as it formed, or it was overridden by the PWT.

I am currently favoring the second interpretation. In this case no NFZ is needed to explain anything observed, at least locally. Everything can be explained by dominantly ductile deformation, at least in the upper crust. This is really reflected in the rocks at Piers Gorge and in the local Michigamme Formation, which locally do not express any Penokean aged faults of any

significance. It also would explain the contemporaneous crustal thinning to the east in the Sudbury area if we had a subducting rift. This is something that forearc extension and island arc accretion cannot explain on their own. This would also put the continental suture further south, at the Eau Claire Shear Zone.

**Figure 1:**



*GPS: 45.75739, -87.94588. Outcrop, sample 101121-1, 0.75 inch (1.91 cm) U.S. quarter for scale. The white inclusion is quartzite. Photo taken by Steven Baumann on October 11, 2021.*

*Adapted from Baumann, 2021*

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## **Paleoproterozoic mantle plume tracks shaping the southern margin of the Superior craton and the geology of the Lake Superior region**

**BLEEKER, Wouter<sup>1</sup>, HAMILTON, Michael<sup>2</sup>, and KAMO, Sandra<sup>2</sup>**

<sup>1</sup>*Geological Survey of Canada, 601 Booth Street, Ottawa, ON K1A 0E8, Canada;  
wouter.bleeker@canada.ca*

<sup>2</sup>*Jack Satterly Geochronology Laboratory, Department of Earth Sciences, University of Toronto, 22  
Ursula Franklin Street, Toronto, ON M5S 3B1, Canada*

All Archean cratons are fragments of late Archean “supercratons”, i.e. the larger landmasses to which these craton fragments trace their origin (Bleeker, 2023). At least two large independent supercratons, Superia and Sclavia, named after their well-preserved internal fragments, had formed by the late Archean and underwent progressive breakup during the early Paleoproterozoic, from ca. 2.2 Ga to 1.9 Ga. Based on well-populated apparent polar wander paths, these supercratons moved independently; hence, the mythical notion of a single, long-lived, late Archean supercontinent “Kenorland” is incorrect, aside from being untestable. Craton fragments can be correlated and put back together again by matching distinctive basement geology, by correlating overlying pre-breakup basin stratigraphies, and by correlating remnants of pre- to syn-breakup large igneous provinces, particularly their dyke swarms (Bleeker and Ernst, 2006). Of all the dispersed Archean craton fragments, more than 10 trace their origin back to supercraton Superia, representing “nearest neighbour” fragments to the Superior: Karelia, Kola, Wyoming, Hearne, Kaapvaal, Pilbara, Yilgarn, Zimbabwe, North Atlantic craton, and possibly Dharwar. Kaapvaal-Pilbara joined a growing Superia late in the game, at ca. 2650 Ma, separating again ~600–700 Myr later, leaving the ancient Minnesota River Valley terrane behind.

With a robust reconstruction of Superia, numerous other important insights follow, including that of ancient mantle plume tracks (Figure 1). Here we discuss evidence for two major plume tracks that shaped the southern margin of the Superior craton, the 2480-2440 Ma “Matachewan” plume track, and the 2125-2050 Ma “Marathon” plume track. Both these plume tracks started within Superia’s core, before crossing over to then-contiguous crust of “greater Karelia” and Kaapvaal, respectively. The Matachewan plume track was initiated in the Sudbury area with a suite of 2480-2472 Ma mafic layered intrusions emplaced at the base of the Huronian Supergroup. It then triggered the ca. 2461 Ma giant Matachewan dyke swarm, which converge to a magmatic centre well to the south. At ca. 2450 Ma, the plume crossed over to then-contiguous “greater Karelia” (Davey et al., 2020) where it spawned additional dyke swarms and a flare-up of large layered intrusions, some as young as 2440 Ma. The much younger Marathon plume was initiated at ca. 2125 Ma with a giant radiating mafic dyke swarm, the Marathon dykes, with a focal point in the eastern Lake Superior area. It then spawned progressively younger mafic dyke swarms to the southwest before crossing over to the contiguous Kaapvaal craton where it spawned carbonatites at 2060 Ma, and finally the emplacement of the Bushveld Complex at 2056 Ma, the long axis of which is aligned with the plume track (Figure 1). Both plume tracks show well-defined age progressions indicating plate velocities of ~1–5 cm/yr.

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# A COMPLEX F-RICH ALKALIC PEGMATITE IN THE PYROXENE SYENITES OF THE STETTIN COMPLEX, WAUSAU COMPLEX, MARATHON COUNTY, WISCONSIN

**BUCHHOLZ, Thomas<sup>1</sup>, FALSTER, Alexander<sup>2</sup>, and SIMMONS<sup>2</sup>, William**

<sup>1</sup>1140 12<sup>th</sup> Street North, Wisconsin Rapids, Wisconsin 54494, <sup>2</sup>MP<sup>2</sup> Research Group, Maine Mineral and Gem Museum, PO Box 500, 99 Main Street, Bethel, Maine 04217, USA

The Stettin Complex is the oldest (1565 ±3-5 Ma, Van Wyck 1994) and most alkalic of the four intrusions that comprise the Wausau Syenite Complex, and is composed of various syenite phases. This abstract is an update to a study of this dike in ILSG 2024.

The sub-horizontal pegmatite is weathered, mineralogically and texturally zoned, and includes numerous syenite screens. Thin 2-3 cm reaction zones are common at contacts, with small miaroles, scattered patches of abundant, tiny pink zircons, fergusonite-(Y), and other minerals. Small miarolitic cavities are common throughout the dike. Overall mineralogy is complex, typical for fractionated alkalic pegmatites.

Pyroxenes are largely absent except for highly altered replacements and sparse unaltered remnants of hedenbergite. Early formed pyroxene(s) appear to have been destabilized by later oxidation, altering Fe<sup>2+</sup>-rich pyroxenes to quartz and smectite-group clays ± goethite with sparse remnants of hedenbergite, and allowing crystallization of more oxidized (Fe<sup>3+</sup> rich) magnetite and arfvedsonite. Similar reactions may have altered early-crystallizing chevkinite-(Ce) (or a similar LREE-Ti species) and possibly aeschynite-(Ce), to an unidentified Ti-Ce<sup>4+</sup>-Fe phase: relatively common soft, pale yellow to creamy to brown grains of varying morphologies typically containing high Ti-Ce-Fe contents with traces of other elements. Cerium is likely present as Ce<sup>4+</sup> based on the absence of associated LREE<sup>3+</sup> (La, Nd, Pr). Alteration under oxidizing conditions may have removed LREE<sup>3+</sup>, Si and other elements, leaving immobile Ti, Ce<sup>4+</sup>, minor Fe<sup>3+</sup> and trace amounts of other elements. Fluorapatite occurs as abundant hexagonal prisms in intermediate zones of the dike; generally highly altered with elevated to very high LREE (Ce-dominant) and Si contents, while similar reddish crystals in pegmatite units near the lower contact show more typical very low LREE contents. This may be the result of alteration/partial replacement of fluorapatite by fluorbritholite as discussed by Betkowski et al (2016). Work also continues on a rare unidentified Ba-silicate mineral, where lack of Al precludes Ba-feldspars.

Several small-volume units and isolated occurrences contain minerals not normally found in alkalic pegmatites, including cassiterite, Hf-enriched zircons (up to 5.5 wt.% HfO<sub>2</sub>, vs 1.48 wt. % HfO<sub>2</sub> in pegmatite margin zircons), fluorcalciomicrocline (D-site occupancy Ta 1.05, Nb 0.65, Ti 0.30; Σ 2), tantalite-(Mn), and barite. Sphalerite in unweathered lower portions of the dike is notable in containing about 0.7 wt. % Indium.

Later oxidizing conditions are evident in late crystallization of siderite (now goethite), and LREE fluocarbonates. Crystallization of fergusonite-(Y) (to date Nb-dominant, ≈Nb 1.96, Ta 0.04; Σ 2), being rich in MREE and HREE and lacking redox sensitive Ce, appears to have continued throughout dike crystallization.

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|                       |                                                                                                                                                                        |              |
|-----------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------|
| Aeschynite-(Ce)       | (Ce,Ca,Fe,Th)(Ti,Nb) <sub>2</sub> (O,OH) <sub>6</sub>                                                                                                                  | Common       |
| Albite                | NaAlSi <sub>3</sub> O <sub>8</sub>                                                                                                                                     | Rock-forming |
| Anorthoclase          | (Na,K)AlSi <sub>3</sub> O <sub>8</sub>                                                                                                                                 | Rock-forming |
| Barite                | BaSO <sub>4</sub>                                                                                                                                                      | Rare         |
| Bavenite(?)           | Ca <sub>4</sub> Be <sub>2</sub> Al <sub>2</sub> Si <sub>9</sub> O <sub>26</sub> (OH) <sub>2</sub>                                                                      | Rare         |
| Bertrandite           | Be <sub>4</sub> (Si <sub>2</sub> O <sub>7</sub> )(OH) <sub>2</sub>                                                                                                     | Rare         |
| Calcite               | CaCO <sub>3</sub>                                                                                                                                                      | Common       |
| Cassiterite           | SnO <sub>2</sub>                                                                                                                                                       | Uncommon     |
| Columbite-(Fe)        | Fe <sup>2+</sup> Nb <sub>2</sub> O <sub>6</sub>                                                                                                                        | Rare         |
| Fayalite              | Fe <sup>2+</sup> <sub>2</sub> SiO <sub>4</sub>                                                                                                                         | Rare         |
| Fergusonite-(Y)       | YNbO <sub>4</sub>                                                                                                                                                      | Common       |
| Fluoro-arfvedsonite   | [Na][Na <sub>2</sub> ][Fe <sup>2+</sup> <sub>4</sub> Fe <sup>3+</sup> ][Si <sub>8</sub> O <sub>22</sub> F <sub>2</sub>                                                 | Rock-forming |
| Fluorannite           | KFe <sup>2+</sup> <sub>3</sub> (Si <sub>3</sub> Al)O <sub>10</sub> F <sub>2</sub>                                                                                      | Rock-forming |
| Fluorapatite          | Ca <sub>5</sub> (PO <sub>4</sub> ) <sub>3</sub> F                                                                                                                      | Common       |
| Fluorite              | CaF <sub>2</sub>                                                                                                                                                       | Common       |
| Fluorcalciomicrolite  | (Ca,Na) <sub>2</sub> (Ta,Nb) <sub>2</sub> O <sub>6</sub> F                                                                                                             | Rare         |
| Fluorcalciopyrochlore | (Ca,Na) <sub>2</sub> (Nb,Ti) <sub>2</sub> O <sub>6</sub> F                                                                                                             | Rare         |
| Graphite              | C                                                                                                                                                                      | Rare         |
| Hedenbergite          | CaFe <sup>2+</sup> Si <sub>2</sub> O <sub>6</sub>                                                                                                                      | Uncommon     |
| Ilmenite              | Fe <sup>2+</sup> TiO <sub>3</sub>                                                                                                                                      | Common       |
| K-feldspar            | KAlSi <sub>3</sub> O <sub>8</sub>                                                                                                                                      | Uncommon     |
| Kainosite-(Y)         | Ca <sub>2</sub> (Y,Ce) <sub>2</sub> (Si <sub>4</sub> O <sub>12</sub> )(CO <sub>3</sub> ) · H <sub>2</sub> O                                                            | Rare         |
| Magnetite             | Fe <sup>2+</sup> Fe <sup>3+</sup> <sub>2</sub> O <sub>4</sub>                                                                                                          | Common       |
| Molybdenite           | MoS <sub>2</sub>                                                                                                                                                       | Uncommon     |
| Monazite-(Ce)         | Ce(PO <sub>4</sub> )                                                                                                                                                   | Common       |
| Niocalite?            | (Ca,Nb) <sub>4</sub> (Si <sub>2</sub> O <sub>7</sub> )(O,OH,F) <sub>2</sub>                                                                                            | Rare         |
| Phenacite             | Be <sub>2</sub> SiO <sub>4</sub>                                                                                                                                       | Rare         |
| Quartz                | SiO <sub>2</sub>                                                                                                                                                       | Rock forming |
| Siderite              | FeCO <sub>3</sub>                                                                                                                                                      | Common       |
| Sphalerite            | ZnS                                                                                                                                                                    | Rare         |
| Thorite               | Th(SiO <sub>4</sub> )                                                                                                                                                  | Rare         |
| Titanite              | CaTi(SiO <sub>4</sub> )O                                                                                                                                               | Uncommon     |
| Zinnwaldite           | KFe <sup>2+</sup> Al(Al <sub>2</sub> Si <sub>2</sub> O <sub>10</sub> )(OH) <sub>2</sub><br>to KLi <sub>2</sub> Al(Si <sub>4</sub> O <sub>10</sub> )(F,OH) <sub>2</sub> | Uncommon     |
| Zircon                | Zr(SiO <sub>4</sub> )                                                                                                                                                  | Very common  |
| Zircon (metamict)     | Zr(SiO <sub>4</sub> )                                                                                                                                                  | Common       |

Table 1. *Dike Mineralogy*

**Micromineralogy and textures in the Sudbury impact layer on the Mesabi Iron Range, Minnesota: record of processes in the proximal-distal ejecta transition zone**  
**CANNON, W. F., STOKES, M. Rebecca, SALERNO, Ross A.**

*U.S. Geological Survey, Geology, Energy & Minerals Science Center, Mail Stop 954, Reston, VA 20192*

The Sudbury Impact Layer (SIL) (1849 Ma), deposited here within hours of the giant meteor impact at Sudbury, Ontario, is known from drill core at four locations on the Mesabi Iron Range (Fig. 1) along a trajectory distance as great as 980 kilometers from the impact point. It records an instant of high energy deposition of about one meter of mixed ejecta and local bedrock within an otherwise quiescent sequence of siltstone and iron formation. Optical, scanning electron microscope, and Raman spectroscopy data provide details of the SIL that reveal some of the complexities of ejecta transport and deposition. Data presented here are from the Nashwauck occurrence where four drill holes provide continuous samples across the layer.

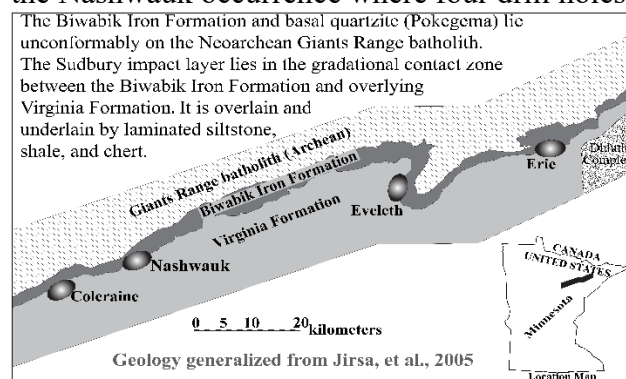


Figure 1. *Geologic map of the Mesabi Iron Range showing the four locations where the Sudbury Impact Layer (SIL) has been observed: Coleraine (Huber, et al., 2014; Nashwauck (Cannon, et al., 2017, this study); Eveleth (Addison, et al., 2005, this study); Erie (this study).*

The SIL on the Mesabi Iron Range consists of millimeter-scale ejecta particles expelled from the large crater near Sudbury, and coarser fragments, of sedimentary rocks, some greater than 3 cm diameter, which were derived locally. The ejecta can be subdivided into two categories: **A-** devitrified glass (Fig. 2), and **B-** millimeter-scale mineral grains and rock fragments displaying shock metamorphic features (Fig. 3).

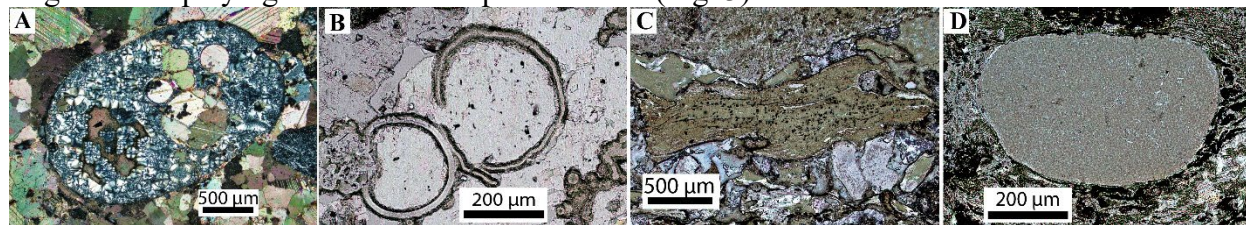


Figure 2. *A-microtektite in matrix of coarse secondary dolomite. Original glass devitrified to K-mica. Vesicles are filled with dolomite. B-delicate bubble structures preserved in secondary dolomite. Bubble walls are mostly K-mica and chlorite. C-angular fragment of flattened vesicular glass, now mostly chlorite. D-rounded particle composed of fine K-mica.*

Spheres of vesicular glass and their fragments are common (Fig. 2A), including thin-walled hollow structures (Fig. 2B). They are now composed of micron-scale K-mica and chlorite. Irregularly shaped glass shards, mostly composed of chlorite, are also abundant (Fig. 2C). Many are larger than typical spherules and are probably far-flung bits of impact melt rather than broken spheres. Most are flattened into bedding. Also common are rounded grains composed of sub-micron K-mica with relict vesicles (Fig. 2D). These are distinct in having been

sufficiently strong to have avoided flattening. Other glass particles are molded around them. They were likely droplets of melt with very uniform K-Al-Si composition.

Quartz and feldspar grains with multiple sets of planar deformation features and zones of devitrified impact glass attest to the intense shock unique to meteor impacts. Small rock fragments with intense shock features are also common (Fig. 3).

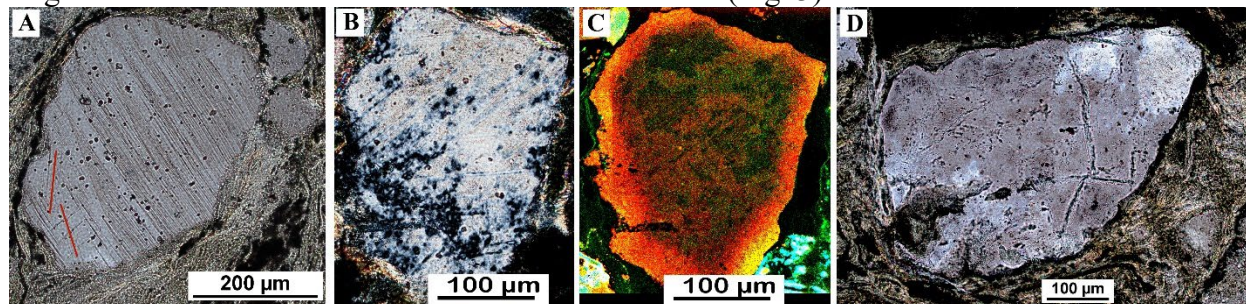


Figure 3. *A-quartz with one well-developed set of planar deformation features and two weaker sets (red lines). B- intensely shocked quartz with “toasted” appearance and zones of devitrified glass. C- cathodoluminescence image of B showing complex shock-induced internal features. D-intensely shocked polycrystalline orthoquartzite fragment.*

Abundant glass spherules in the Nashwauk ejecta appear to be microtektites. Such particles are widely interpreted to form by condensation from impact vapor plumes above the atmosphere and can be distributed worldwide. At Nashwauk they are mixed with small rock and mineral particles from the outermost margins of the impact ejecta curtain. These were transported either (or both) on ballistic trajectories, or by intense impact-generated winds beyond the ejecta curtain. Many have strongly developed shock features attesting to their derivation by crater excavation near Sudbury. Notably missing from the SIL on the Mesabi Iron Range are accretionary lapilli, a hallmark of more proximal sites where ballistic ejecta and ground surges were the dominant transport mechanism for ejecta. The SIL at Nashwauk is very similar to that at the three other occurrences along the Mesabi Iron Range which, together, document a broad transition zone, between about 900 to 1000 kilometers from the impact point. Here the most distal ballistic ejecta persisted as millimeter-scale grains into a zone where ejecta plume material was becoming dominant. Along the Mesabi Iron Range ejecta was deposited in a shallow sea where fine-grained laminated silt and chert were being deposited, both before and after the impact. Strong impact-generated tsunamis reworked the ejecta and underlying sediments within hours or days of the impact to produce the intermixing of fine-grained ejecta particles with much coarser rip-up clasts from the pre-impact seabed.

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## Updates on the Minnesota Department of Natural Resource's Drill Core Library

**CARTER, Matt<sup>1</sup>**

<sup>1</sup>*Minnesota Department of Natural Resource, Division of Lands and Minerals, 1525 3<sup>rd</sup> Ave E, Hibbing, MN, 55746 USA*

The Minnesota Department of Natural Resource's (DNR) Drill Core Library (DCL) in Hibbing, MN is the only state-owned facility for archiving drill cores and other geological materials from Minnesota. The DCL was first established in 1972 when Building 1 (B1) was constructed. It was expanded in 1979 when Building 2 (B2) was constructed. Building 3 was first constructed in 1989 and expanded in 1995 and 2009. The facility currently stores around 3.5 million linear feet of drill core and contains material and/or data for over 20,000 drillholes. In 2023, it was identified that original shelving units installed in B1 and B2 needed to be replaced, and other safety issues needed to be resolved.

The DNR diligently prepared to move all drill cores and other noncore geological materials from B1 to replace the shelving units. This was accomplished by assessing materials for deaccession, creating a box index of its holdings, applying barcodes to over 38,000 drill core boxes, as well as inventorying and barcoding noncore materials. Boxes were moved box by box by hand onto roller tables to an intake station where tracking information and digital images were captured. Boxes were then palletized and placed into temporary storage, which involved 712 pallets and 40 storage containers. The captured digital images have created a new and accessible digital record for B1 cores. Once the original shelving units were removed from B1, the DNR upgraded its lighting, and a new racking system was installed. Reverse flow of materials to B1 is anticipated to be completed by the end of May.

Similar preparation activities are being applied on materials in B2. Instead of placing materials into temporary storage, rack space will be freed up through deaccession activities and materials will be rearranged within B2 to create new egress space. Over 210,000 iron ore boxes will be repackaged and moved onto new rack units. Lighting upgrades have been implemented in portions of B2, with the remaining lights to be replaced later this year. The DCL remains partially open to visitors, but users should be aware that materials from B1 and B2 may be unavailable until the project is completed on or before June 30, 2026.

The DCL is nearing its facility-wide storage capacity and there is very limited space to accept additional materials. The DNR is only accepting deliveries on a case-by-case basis, and it is expected that any materials turned over to the state will become public upon delivery. In 2017, recognizing that the DCL was rapidly filling up, the DNR designed and actively sought funding for a fourth building to double the facility-wide storage capacity and quadruple view room space. This project is shovel-ready, but construction remains on hold until funding is legislatively secured.



## **Geology and Mineralization of the Plover Au Prospect, Marathon County, Wisconsin CASPER, Andrew A.<sup>1</sup>, LODGE, Robert W.D.<sup>1</sup>**

<sup>1</sup>*Department of Geology and Environmental Sciences, University of Wisconsin-Eau Claire, Eau Claire, WI 54701 USA*

The Plover Au Prospect, located in Marathon County, WI, is hosted in Paleoproterozoic metaandesites, schist, and felsic/mafic intrusive units of the Wausau Volcanic Complex (LaBerge & Myers, 1983). Gold prospects in this region are bound to the southeast and northwest by large faults within the Eau Claire Deformation zone and the Wolf River Batholith (Lynott et al, 2022) (Figure 1). Rocks have undergone potassic and sericite alteration, greenschist to amphibolite grade metamorphism, and multiple stages of deformation. Research on the formational history of gold mineralization, in combination with its geochemical footprint, is essential for establishing a regional geologic setting of gold-forming events. Previous mineral exploration on this area has focused on exploring high concentrations of gold (Au) within volcanic units and sulfide vein networks at the Reef Deposit (Figure 1). With its proximity to the larger Reef Deposit, a more complete understanding of the Plover Prospect can add to a better regional context to the Au mineralizing system and potentially improve mineral exploration models.

For this study, two holes (PL-76-1 & PL-76-4), totaling ~1,180 linear feet of core were chosen based on their relative locations and lithologic variation to fully characterize the range of units hosting mineralization. Representative volcanic strata and intrusive rocks were sampled and characterized through petrographic and geochemical analyses. The Plover deposit is primarily composed of andesitic/basaltic volcanics and gabbro/diorite intrusive units deposited sequentially showing sharp and, in some cases, brecciated contacts with one another. Brittle-ductile deformation is indicated by zones of brecciation present within the volcanic units. These structures include vein networks containing boudins and vugs containing sulfides and calcite-chlorite alteration. It is probable that multiple deformational events occurred due to veins cross-cutting foliation locally, and variation in the internal composition of veins. Hydrothermal alteration is suggested based on the presence of potassic alteration within the basaltic foliation and sericite-chlorite alteration in layers. Pyrite, chalcopyrite and pyrrhotite occur within vein networks. Since high Au concentrations are typically present within massive/semi-massive sulfide veins which contain brittle to brittle-ductile deformation, this mineralization likely occurred after Penokean deformation and metamorphism that formed the primary structural fabric in the rocks.

The Reef gold-copper deposit has been researched extensively by various exploration companies since the 1990's (Lynott et al, 2022). The deposit is located <1 mi east of the Plover deposit and has shown significantly higher Au concentrations. The deposit has been broadly classified as orogenic in origin and is claimed to have produced shear hosted vein-type gold and copper occurrences. Gold/copper mineralization occurs within stacked and relatively thin zones of quartz-sulfide veins and lenses; and sericite alteration within vein selvage typically accompanies gold mineralization within these areas. The primary lithology between the two deposits is similar, however, the Reef deposits proximity to the Wolf River batholith potentially influenced the degree of deformation and sericite, talc, tremolite, and pyrrhotite alteration. Future research should focus on more detailed comparisons between the Reef and Plover gold systems to better constrain potential genetic links between them.

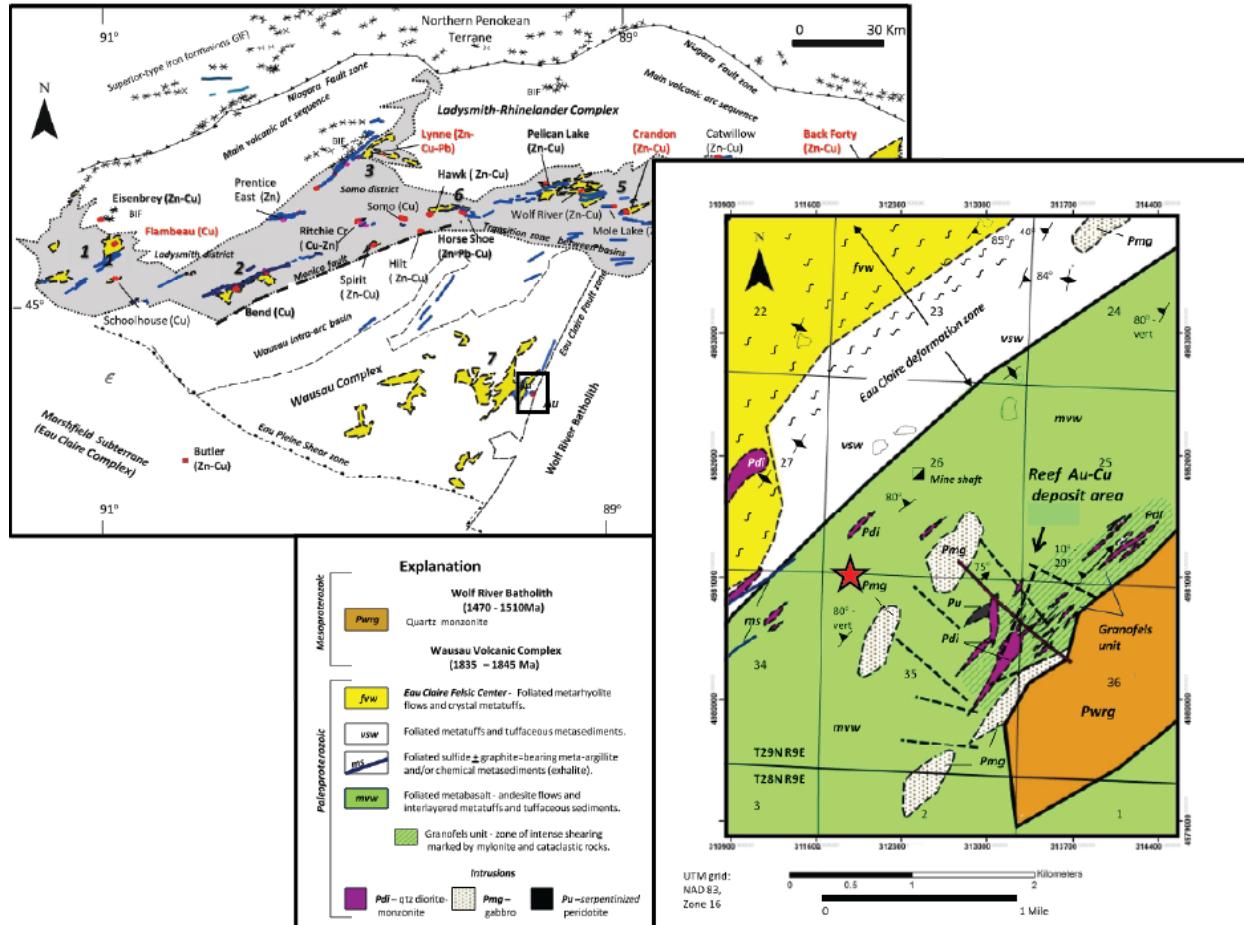


**Figure 1.** The relative geographic locations of the Plover and Reef deposits in the Penokean Volcanic Belt (PVB), central Wisconsin. Plover Au prospect is bounded to the east by the Eau Claire fault zone and the Wolf River Batholith. Figure has been adapted from Dematties (2022) and Lynott et al, (2022).

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## Unusual early diagenetic structures in the Paleoproterozoic Gunflint Formation, Ontario, Canada

CHURCHLEY, Sophie<sup>1</sup>, FRALICK, Philip<sup>2</sup>

<sup>1</sup>Ontario Geological Survey, 435 James St S, Suite B002, ON P7E 6S7 Canada

<sup>2</sup>Department of Geology, Lakehead University, 955 Oliver Road, Thunder Bay, ON P7B 5E1 Canada

Newly identified microbial and diagenetic structures in the Gunflint Formation from the Thunder Bay area provide additional information to further our understanding of the environment in which these sediments were deposited and the diagenetic processes that affected them. Along the Current River, a horizon of carbonate lenses outcrop within a shale sequence. The structures are oblate in shape and range from approximately 0.5-1 m in diameter and 20-30 cm in height. Internally, the lenses are mostly calcite that displaces fine-grained siliciclastic laminae and preserves several interesting structures including cone-in-cone, inverted cusped fenestrae and feather-like and braided fabrics. Some faces also display features that are more ‘fern-like’ in appearance and migrate up and across the surface of the oblate carbonate pods. We propose that these are oblate carbonate concretions formed via carbonate precipitation during diagenesis within a sequence of organic-rich laminated shales and siltstones. Several important features observed in the Gunflint Formation suggest that these structures formed via diagenetic processes including the similarities in stratigraphic placement within organic-rich shaley horizons and the light  $\delta^{13}\text{C}_{\text{carb}}$  values recorded in the carbonate fraction.

Cone-in-cone structures have been identified in both hand sample and thin section, displaying similarities to structures described from other locales (Figure 1A,B). Cone-in-cone structures occur in calcite-cemented sandstones or at the edges of disc-like to ellipsoidal concretions ranging in size from decimeters to meters long within shale beds in Erfoud, Morocco (Lugli et al. 2005). This stratigraphic positioning and size is consistent with what has been observed in the Gunflint Formation oblate concretions that host the cone-in-cone layers. Likewise, jagged ‘saw-toothed’ draping laminae that were identified in the Gunflint Formation are similar in appearance to those identified from cone-in-cone structure in the Devonian Middle Timan Formation in Russia (Figure 1C,D) (Shumilov 2020).

The formation of cone-in-cone structure is still not well understood and numerous hypotheses have been proposed (see Lugli et al. 2005 and references therein). It is commonly associated with concretions and organic-rich sediments. The oblate carbonate horizons are located stratigraphically within a sequence of carbonaceous black shales near the base of the Upper Member of the Gunflint Formation with abundant evidence of microbially induced sedimentary structures (MISS) (Fischer and Fralick 2020).  $\delta^{13}\text{C}_{\text{carb}}$  analyzed from the carbonate fraction in the Gunflint Formation samples displayed light values ranging from -12.29‰ to -0.17‰ with most values clustering near -10‰. These values are coincident with precipitation occurring in the zones of Fe, Mn, and/or sulfate reduction with relatively low rates of organic-carbonate oxidation and are consistent with ferruginous, reducing conditions (Mozley and Burns 1993).

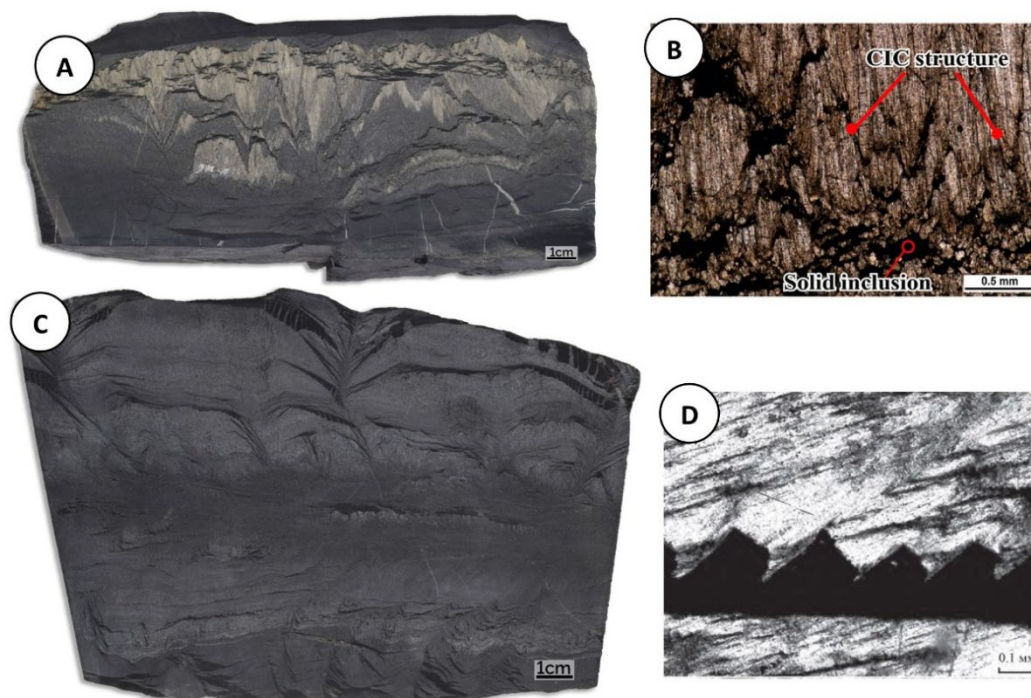


**Figure 1.** *A. 1-3 cm scale cone-in-cone structure consisting of beige fibrous calcite draped by thin black siliciclastic films. B. Thin section close up of cone-in-cone structure from Permian carbonates in Thailand that is similar in appearance to those observed in the Gunflint Formation (see figure 3C; Chenrai et al. 2022). C. Hand sample of a carbonate-rich horizon displaying jagged 'saw-toothed' laminae near the top. D. Close-up image of similar jagged laminae from the Devonian Middle Timan Formation in Russia (see figure 9A; Shumilov 2020). At this location, the jagged laminae are associated with cone-in-cone structure.*

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## **Alteration of magnetic mineralogy in the Giants Range Batholith by the Duluth Complex**

**CORTOPASSI, Celia L., ALLERTON, Zsuzsanna P., FEINBERG, Joshua M.**

*Department of Earth and Environmental Sciences, University of Minnesota, Suite 150, 116 Church St SE, Minneapolis MN 55455*

During the Midcontinent Rift event (ca. 1.1 Ga) of the North American craton, the Duluth Complex (DC), a large mafic igneous intrusion, was emplaced into the Neoarchean Giants Range Batholith (GRB; ca. 2.7 Ga) in northeastern Minnesota, thermally altering the granitic country rock (Allison, 1925). The basal mineralized zone of the DC has been well-studied with regard to sulfide deposits, but the extent of alteration within the GRB footwall has not been as well constrained. Previous research has indicated the presence of sulfides at the DC-GRB contact, extending about hundred meters into the GRB (Steiner, 2014), and prior petrographic analysis has revealed textures consistent with contact metamorphism that diminish with distance from the contact (Pardi, 2024). This project seeks to define the magnitude of alteration within the GRB and to further characterize the orientation of the intrusion.

This project utilizes a profile of 13 outcrop samples from the GRB that were collected systematically at distances between 100 and 4500 meters from the DC-GRB contact. We characterize changes in magnetic mineralogy as a function of distance from the DC-GRB contact using measured optical microscopy, electron microscopy, and magnetic properties (susceptibility and parameters calculated from hysteresis loops and backfield curves). These data reveal a distinguishable and consistent pattern in magnetic properties as a function of distance from the contact and distinct zones of textural alteration in oxide minerals (Figure 1). Patterns in small-scale magnetic properties broadly align with the large-scale trends seen in aeromagnetic data (Minnesota Geological Survey, n.d.), including changes in magnetic properties co-located with mapped faults (Jirsa et al., 2011).

The orientation of the DC-GRB contact was examined using information from previously-drilled exploration drill holes (Minnesota Department of Health, n.d.) that penetrated through the DC and into the GRB. These observations, as well as outcrop measurements of modal layering and igneous foliation within the DC (Minnesota Geological Survey, 2023), constrain the orientation of the present-day DC-GRB contact to between 16-24° towards the east. The original depth of the modern day exposure of the DC-GRB remains unknown, as does any component of subsidence that occurred since the Midcontinent Rift event.

Future work may include the collection of oriented samples for paleomagnetic studies, which would help constrain both the extent of thermal reheating of the GRB and post-emplacement subsidence. Thermal modeling of the subsurface DC-GRB contact at various depths, alongside observed patterns in oxide mineral textures, could produce estimates of the extent of subsurface contact metamorphism. With these methods, we hope to better understand the conditions under which the DC was emplaced and accommodated, as well as estimate the thickness of Precambrian rock that has since been eroded away.

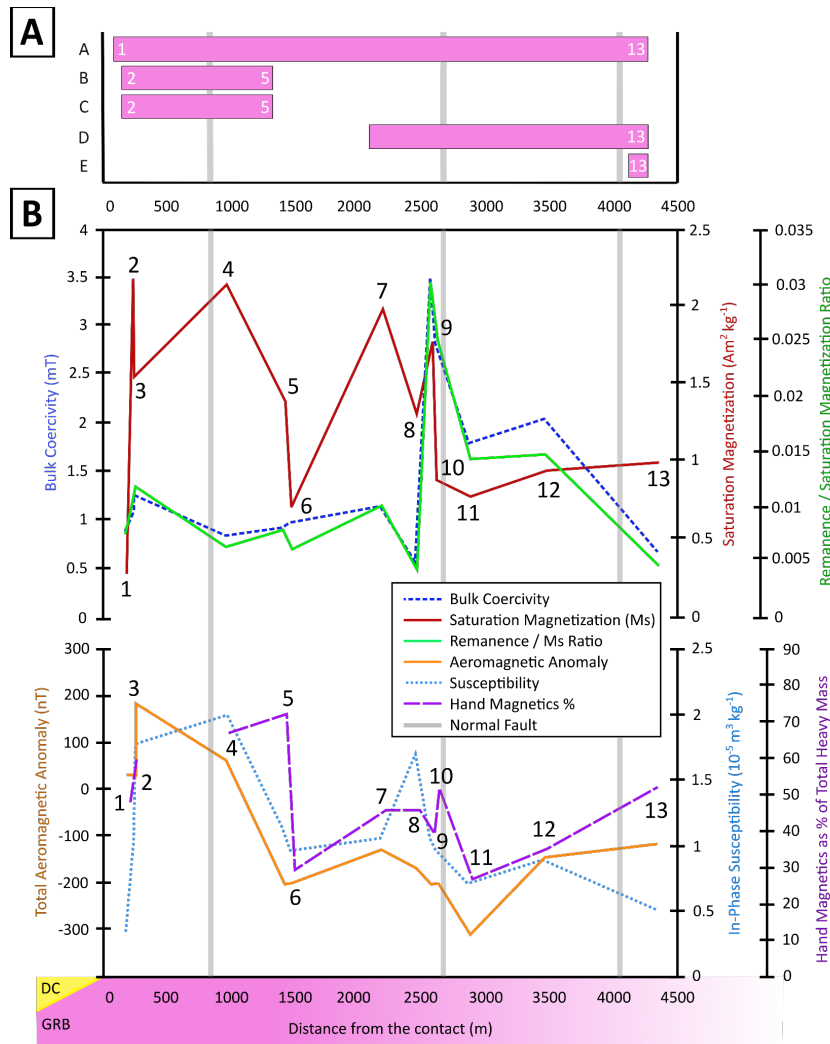


Figure 1. **A:** Distribution of identified textures (A-E) as a function of distance from the DC-GRB contact. **B:** Measured magnetic properties as a function of distance from the DC-GRB contact.

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## Architecture of the Douglas Fault damage zone, northwest Wisconsin

**DANIELS, Nate, MCELLISTREM, Grace, VOGEL, Raeann, and BRAUNAGEL, Michael**

*Department of Earth & Environmental Sciences, University of Minnesota Duluth, 1114 Kirby Drive  
Duluth, MN 55812 USA*

Major faults in the upper crust can be divided between the fault core, where most of the displacement is accommodated, and a surrounding damage zone (Faulkner et al., 2010). Fracturing in this damage zone occurs across a range of scales and intensity, varying from regularly spaced joint or deformation band sets to pervasive pulverization of the host rock. As such, fault damage zones can serve as fluid pathways, which control the migration of hydrothermal fluids and can alter the frictional strength of seismogenic fault systems. A number of processes are responsible for formation and evolution of a fault's damage zone, including microfracturing within the process zone during fault propagation, localized wear along irregular fault surfaces, and volumetric changes associated with dynamic rupture propagation (Mitchell & Faulkner, 2009). As each process leaves a unique record in the fault system, the distribution and intensity of fault damage zones can provide insight into past fault activity and its relationship to fluid flow in the crust (Blenkinsop, 2008). This study presents preliminary observations of the fault-related damage surrounding the Douglas Fault from Amnicon and Pattison State Parks in northwestern Wisconsin. The Douglas Fault was activated during structural inversion of the Midcontinent Rift and previous work estimates its vertical displacement at  $\geq 10$  km (Grant, 1901; Cannon, 1994; Nicholson et al., 2006; Hodgins et al., 2024). At our study sites, the fault places basalts of the mid-continental rift Chengwatana volcanic group over post-rift siliciclastic sandstones of the Bayfield Group.

Field and thin section observations along the fault system reveal pronounced damage zone asymmetry, with a hanging wall damage zone that is several times the width of the damage zone in the footwall. Chengwatana volcanics in the hanging wall are intensely fractured at the grain scale and cut by multiple generations of primarily calcite-filled opening mode veins. These veins and fractures broadly show two distinct orientations; one set striking generally NE to SW and the second characterized by NW to SE strikes. The damage-zone width is constrained by identifying changes in the slope of cumulative damage frequency plots, which shows high deformation frequency as a steep slope within an inner damage zone and less deformation decaying to background levels as a gentle slope in the outer damage zone of the Douglas Fault. Collectively, the full thickness of the hanging wall damage zone is  $>100$  m (Grant, 1901). In contrast, sandstones of the Bayfield Group in the footwall exhibit lower frequency fracturing at the outcrop scale, no apparent grain-scale fracturing in thin section, and compressional deformation bands defined by porosity reduction. Bayfield sandstones in the footwall at these sites are also deformed by fault-propagation and drag folding that extend for tens of meters beyond the fault contact (Hodgins et al., 2024). Field and thin section scale observations of fault damage in both units are consistent with ultrasonic pulse velocities measured in samples collected from the fault zone with a Proceq Pundit Lab system.

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## **The Archean Carney Lake gneiss complex in Michigan's Upper Peninsula: Preliminary subdivisions with age constraints**

**DeGRAFF, James<sup>1</sup>, DEERING, Chad<sup>1</sup>, and JONES III<sup>2</sup>, James**

<sup>1</sup>*Department of Geological & Mining Engineering & Sciences, Michigan Technological University, 1400 Townsend Drive, Houghton, MI 49931 U.S.A.*

<sup>2</sup>*U.S. Geological Survey, Alaska Science Center, 4210 University Drive, Anchorage, AK 99508 U.S.A.*

Much of the Precambrian bedrock in Michigan's Upper Peninsula was last mapped at 1:24000 scale prior to modern tectonic concepts and advances in understanding related structural, magmatic, and metamorphic processes. A later decline in base and ferrous metal mining in the region reduced interest in commercial and scientific investigations, however recent concerns about the supply of critical minerals has renewed interest in developing an improved geologic framework for ore deposit exploration. The Archean Carney Lake gneiss complex (CLGC) and other granite-gneiss complexes south of the Great Lakes tectonic zone are in the Minnesota River Valley subprovince of the southern Superior craton (Sims and Day, 1993). The CLGC, like the other complexes, is surrounded by Paleoproterozoic continental margin strata, partly older than and partly coeval with Penokean orogenesis (~1.85 Ga) that deformed the region (Schulz and Cannon, 2007). Bayley et al. (1966) describe the CLGC as predominantly felsic gneiss but with ~10% mafic inclusions and ~5% younger granodiorite and syenite intrusions by area.

Mapping funded by the USGS Earth MRI program has revealed a wider variety of rocks than previously reported, differences in metamorphic grade, and new structural relationships (DeGraff et al., 2023). Felsic intrusions with little to no foliation are more abundant and varied than previously thought, ranging from granitic to tonalitic to locally syenitic. The original classification of gneiss based on mineralogy has been revised by also considering fabric characteristics. Consequently, we have identified an older EW-elongate core of thickly banded ( $\geq 2$  cm) poly-deformed gneiss characterized by tightly folded banding, discordant banding across shear zones, and dismembered mafic pods (Fig. 1, area 1). Younger, less deformed, Archean rocks flank the older terrane, except on the north, and include the widespread felsic intrusions and thinly banded ( $\leq 1$  cm), quartzo-feldspathic, gneissic rocks. The latter have quasi-planar, laterally continuous banding and local textures resembling cross-bedding and relict grains, suggesting derivation from a siliciclastic protolith. Boundaries between the older deformed gneiss terrane, the younger gneissic terrane with relict features, and areas with felsic intrusions are not yet well defined nor is their nature well understood. In addition to the above, at least four generations of mafic to ultramafic magmas have intruded the CLGC up to the late Mesoproterozoic.

Our results, combined with those of others, indicate a long and complex tectonomagmatic history for the CLGC and adjacent rock units. The poly-deformed gneiss terrane includes rocks with inherited zircon cores dated at ca. 3750 Ma (Eoarchean) and recrystallized zircons and overgrowths dated at ca. 2750 Ma, the latter having formed during a Neoproterozoic thermal event (Ayuso et al., 2018). Neoproterozoic metamorphism of the Eoarchean gneiss, and perhaps much of its deformation, was accompanied by widespread felsic intrusions based on new zircon LA-ICPMS U-Pb dates ranging from ca. 2810 Ma to 2670 Ma (8 sites). Zircon trace-element analysis indicates that these magmas came from a hydrous oxidizing source and were contaminated while passing through a relatively thick crust, as is typical of magma generated during modern subduction. At the northern and eastern margins of the CLGC, relatively undeformed gneissic rocks were probably derived in part from siliciclastic protoliths of Neoproterozoic age. At the northern margin,

however, NE-dipping beds of Paleoproterozoic Sturgeon Quartzite are parallel to well-defined layers of quartzo-feldspathic gneissic rocks along strike to the east. Field relationships and detrital zircon analysis suggest two scenarios: 1) a lateral facies change within Sturgeon Quartzite from meta-arkose on the east to meta-sandstone on the west, or 2) an onlapping relationship between younger quartzite and its parent Neoproterozoic meta-arkose.

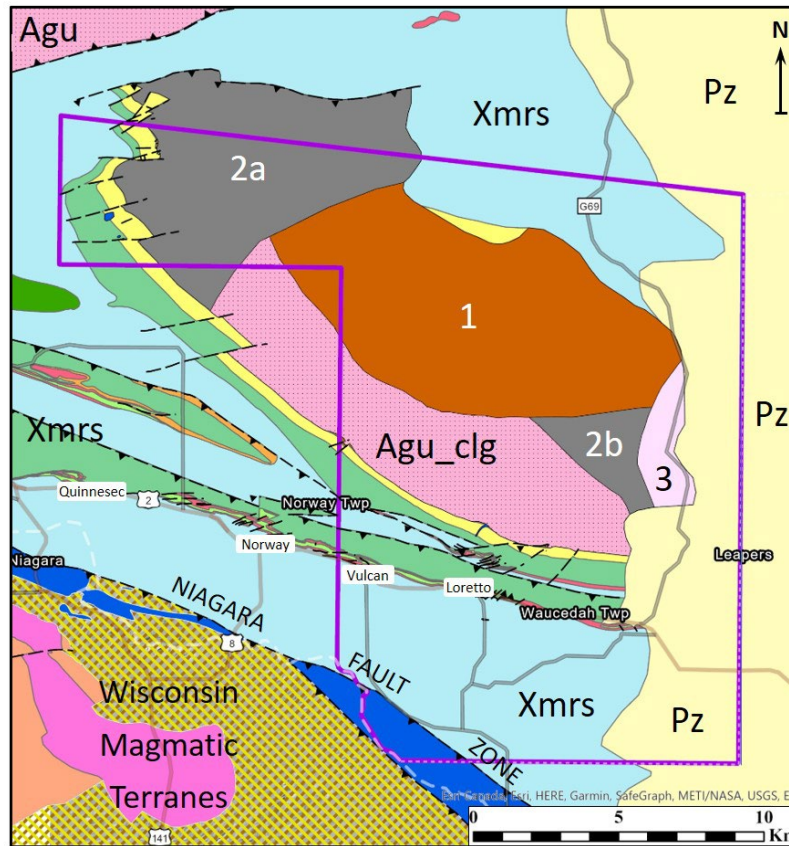


Figure 1: Preliminary subdivisions of the Archean Carney Lake gneiss complex (CLGC = 1, 2a, 2b, 3, Agu\_clg). 1 = poly-deformed; 2 = meta-igneous, 3 = meta-sedimentary; Agu\_clg = undifferentiated; Xhrs = Paleoproterozoic Marquette Range Supergroup; Pz = Paleozoic clastic strata. Study area outlined in purple.

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**Geochronology of lithium mineralization in the Florence pegmatite field, WI, USA**  
**DROUBI, Omar Khalil<sup>1</sup>, SCHOONOVER, Erik<sup>2</sup>, SIRBESCU, Mona-Liza<sup>3</sup>, GARBER, Joshua<sup>2</sup>, BONAMICI, Chloë<sup>1</sup>**

<sup>1</sup>Department of Geoscience, University of Wisconsin-Madison, 1215 W. Dayton Street, Madison, Wisconsin, 53706, USA

<sup>2</sup>Department of Geosciences, The Pennsylvania State University, University Park, PA, USA

<sup>3</sup>Geology Department, Central Michigan University, 314 Brooks Hall, Mount Pleasant, MI 48859, USA

Global and national progression toward decreasing reliance on fossil fuels will correlate with increasing the supply of mineral resources that contain high concentrations of elements like lithium, copper, or rare earth elements—“critical minerals” deemed essential for building low-CO<sub>2</sub> technologies. Lithium-cesium-tantalum (LCT) pegmatites are a significant component of global lithium production; despite their importance, the tectonomagmatic mechanisms by which these pegmatites form are not completely understood. The two main models for LCT pegmatite formation are 1) as late-stage fractionation products of nearby peraluminous granites (“fractionation origin”) (e.g., Černý, 1991) or 2) directly from partial melts of Li-bearing high-grade metamorphic rocks (“anatectic origin”) (e.g., Knoll et al., 2023; Koopmans et al., 2023). These models have implications for LCT pegmatite exploration (i.e., mapping outward from plutons or anatectic zones in mountain belts) and testing them requires precise age estimates for the pegmatites and their neighboring magmatic and metamorphic rocks.

This study provides new age constraints for models of LCT pegmatite mineralization in Florence County, WI, USA. (Falster et al., 2005; Falster et al., 1996; Sirbescu et al., 2008) by applying LA-ICP-MS U-Pb geochronology and trace-element analysis to apatite crystallized within the LCT pegmatites and titanite in the proximal wall rock and a separate, non-mineralized granitic pegmatite located >1.8 km away (Figure 1). The Florence LCT pegmatites were emplaced <2.5 km south of the Niagara Fault Zone and are hypothesized to be fractionated products from the nearby Bush Lake granite (undated, but hypothesized ~1835 Ma; Sims et al., 1985) or anatectic melts of the wall rock, the metavolcanic/metasedimentary Quinnebec Fm. (~1866 Ma; Sims et al., 1985). These models suggest pegmatite emplacement is broadly bracketed in space and time by the end of the Penokean orogeny (~1835 Ma) and Yavapai arc accretion (~1750–1700 Ma) (Figure 1). The apatite grains from the King’s X and Animikie Red Ace LCT pegmatites have U-Pb dates of  $1446 \pm 6$  [29] Ma and  $1432 \pm 4$  [29] Ma, respectively. The targeted apatite grains, which nucleated in the pegmatite chilled margin at the wall rock contact, are interpreted as magmatic based on oscillatory cathodoluminescence zoning (Sirbescu et al., 2009). Xenoblastic titanite from the Quinnebec Fm., sampled at distances <1 cm to ~150 m from the pegmatites, have U-Pb ages of  $1473 \pm 7$  [29] Ma (<1 cm),  $1466 \pm 7$  [29] Ma (<5 m),  $1436 \pm 13$  [29] Ma (60 m), and  $1471 \pm 8$  [29] Ma (150 m), but euhedral titanite grains from the non-mineralized granitic pegmatite have a U-Pb age of  $1811 \pm 10$  [36] Ma. Our data indicate that the Florence LCT pegmatites did not result from fractionation of the Bush Lake granite nor anatexis during the Penokean or Yavapai orogenies and are instead coeval with emplacement of the ~1476 Ma Wolf River batholith further south. A revised age model for lithium mineralization in northern WI suggests involvement of the Wolf River batholith or far-field influence of the Mesoproterozoic Pinware-Baraboo-Picuris orogeny.

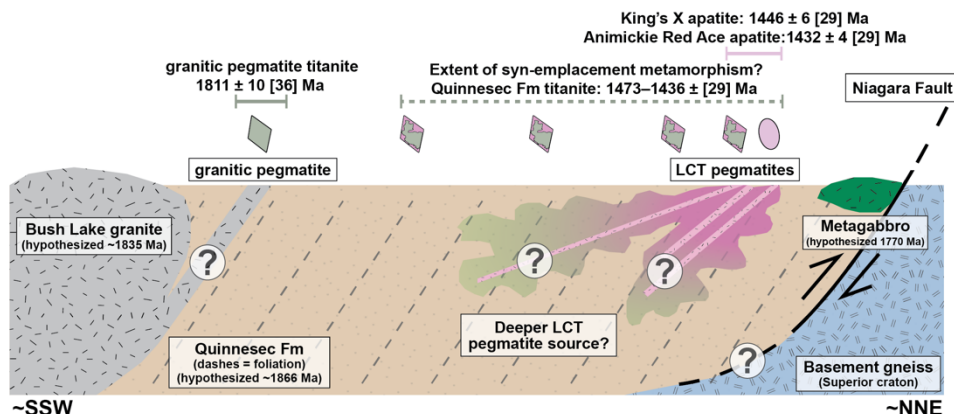


Figure 1. Conceptual cross section (not to scale) showing age constraints for the Florence pegmatite field. Hypothesized ages based on the following references: Bush Lake granite and Quinnesec Fm. (Sims et al., 1985), metagabbro (Guice et al., 2023). U-Pb dates reported as: date  $\pm$  internal 2s [external uncertainty=2% of date].

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# Experimental Reproduction of Acidic Mafic-Ultramafic Hydrothermal Fluids with Implications for Linking Seafloor Lithology to Ore Mineral Solubility and Novel Geochemical Trapping Mechanisms

EVANS, Guy N.<sup>1</sup> and SEYFRIED JR., William E.<sup>1</sup>

<sup>1</sup>*Department of Earth and Environmental Sciences, University of Minnesota, 116 Church St SE, Minneapolis, MN, 55455, United States*

Ultramafic-hosted seafloor massive sulfide (UM-SMS) deposits constitute a distinct class of Cu-Zn-Co-Ni-Au-rich seafloor hydrothermal deposits (Fouquet et al., 2010). However, ultramafic-hosted volcanogenic massive sulfide (UM-VMS) deposits have been historically overlooked, in part because the formation of UM-VMS deposits differs from traditional VMS genetic models based on basalt-hosted SMS deposits (Pattern et al., 2022). Adding to this complexity, ultramafic-hosted seafloor hydrothermal fluids span nearly the full range of pH and metal concentrations observed at active seafloor hydrothermal vents, from highly acidic (pH= 2.8), metal-rich (Fe > 20 mmol/kg) fluids observed at Rainbow Hydrothermal Field (Douville et al., 2002), to alkaline (pH = 10.5), metal-poor (Fe < .02 mmol/kg) fluids observed at Lost City Hydrothermal Field (Kelley et al., 2005; Evans et al., 2024).

Here, we present results from recent experiments conducted at the University of Minnesota that for the first time reproduce acidic hydrothermal fluids from mixed mafic-ultramafic source minerals. The observed acidity of these fluids results from temperature-dependent fluid-rock reactions and superimposed geochemical and physical processes. We further highlight the implications of these findings for UM-VMS deposit models, including novel geochemical trapping mechanisms potentially relevant in areas exhibiting significant ultramafic volcanic/intrusive rocks. Regional examples include the Newton Belt (northeast Minnesota), Shebandowan Belt (northwestern Ontario), and Kidd-Monroe assemblage (eastern Ontario and Quebec).

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## **Textural and chemical analysis of sphalerite ores from the Highland Subdistrict, Upper Mississippi Valley Zinc-Lead District, Wisconsin**

**FITZPATRICK, William<sup>1</sup>**

<sup>1</sup>*Wisconsin Geological and Natural History Survey, 3817 Mineral Point Rd. Madison, WI, USA*

Lead + zinc  $\pm$  barite  $\pm$  copper deposits are widespread in Ordovician carbonate rocks of southwestern Wisconsin and the bordering areas of Illinois and Iowa, commonly referred to as the Upper Mississippi Valley zinc-lead district (UMVD). Sphalerite, the primary zinc ore mineral in the UMVD, is known from other mining districts to contain valuable byproduct commodities as trace elements such as gallium, germanium, cadmium and silver. Several previous studies have examined sphalerite from the UMVD, but focused on samples from the southern part of the district (Hall and Heyl, 1968, McLimans and others, 1980). Zinc ores from other areas of the UMVD have received less attention, and little is known of their textural character and trace element content. This study presents new trace element data and textural observations of sphalerite ores from the Highland Subdistrict, the northernmost mining center in the UMVD. Two hand-picked sphalerite concentrates and thirty-five bulk ore samples were analyzed by whole rock geochemical methods, complemented by 282 in situ electron microprobe analyses on six thin sections from a mix of vein and disseminated ores. Textures in the sphalerite ores were also documented through scanning electron microscopy with the aim of understanding mechanisms that localized sulfide mineralization.

Sphalerite from the Highland Subdistrict is characterized by alternating sequences of lighter, honey-colored bands and darker, reddish-brown bands in both the disseminated and vein hosted ores (Fig. 1). Microprobe analysis shows that darker bands tend to localize elevated iron and lower cadmium relative to lighter bands (Fig. 1). Silver content is variable, but tends to be higher in lighter bands, especially in the cores of disseminated grains. Comparing results from the whole rock and microprobe analyses from the Highland Subdistrict to sphalerite analyzed elsewhere in the UMVD, iron and cadmium are within known ranges, but silver is enriched to a significant degree (Hall and Heyl, 1968). Gallium and germanium abundances were too low to be detected in microprobe analyses, but whole rock analysis indicates they are towards the low end of the range observed in sphalerite from the UMVD (Hall and Heyl, 1968).

Scanning electron microscope observation discovered abundant, texturally early framboidal pyrite intergrown with marcasite that is enveloped by later sphalerite. Framboidal pyrite has a well-documented association with sulfate reducing bacteria (e.g. Maclean and others, 2008), indicating bacterial processes were likely important in creating a reservoir of reduced sulfur within the carbonate host rocks. This in turn may have acted as a chemical trap for metals in migrating connate brines to form the zinc deposits.

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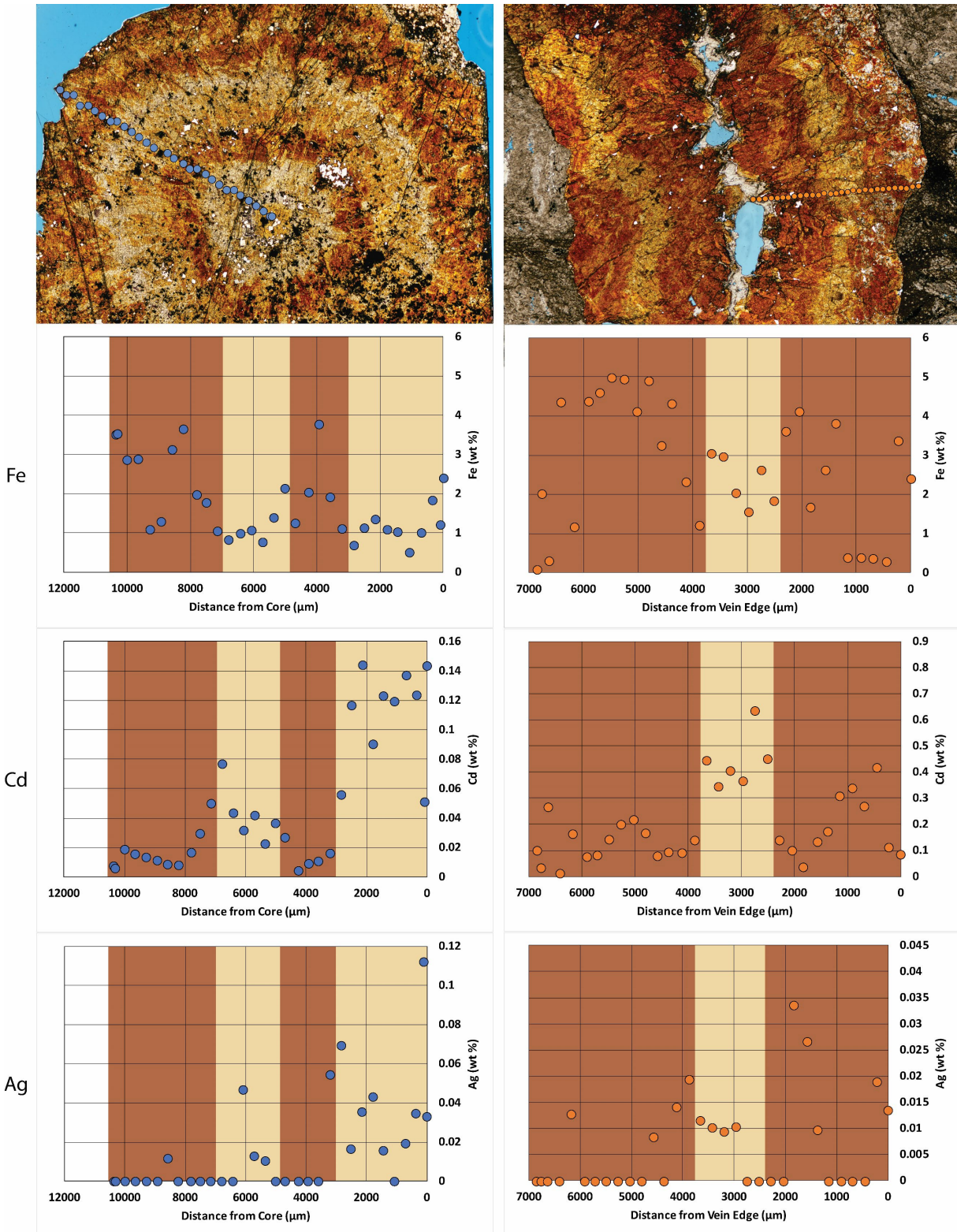


**Figure 1.** Plots of iron, cadmium and silver along linear traverses through banded sphalerite crystals from the Highland Subdistrict. Top panel shows scans of the thin sections analyzed and locations of the analyses. Note the concentrically zoned disseminated grain (left) vs vein (right).

## Rare-element Geochemistry of the Eau Claire River Complex Pegmatites

**GRIES, Samara<sup>1</sup>, LODGE, Robert W.D<sup>1</sup>, HANEL, Sara<sup>1,2</sup>, HOOPER, Robert<sup>1</sup>**

<sup>1</sup>*Department of Geology and Environmental Sciences, University of Wisconsin-Eau Claire, Eau Claire, WI 54701 USA*

<sup>2</sup>*Current Affiliation: Department of Earth and Environmental Sciences, University of Minnesota Twin Cities, Suite 150, 116 Church St. SE, Minneapolis, MN 55455*

Minerals, such as monazite and xenotime, are an important source of rare earth (La, Ce, Nd) and high field strength (Th, Nb, Zr) elements which are essential for modern energy, communication, and military technologies. These critical minerals are often sourced in pegmatites and are important exploration targets worldwide (Haque et al, 2014). The Paleoproterozoic Eau Claire Volcanic Complex (ECVC) is intruded by granitic pegmatite dikes that postdate peak metamorphism (Lodge et al, 2023), indicating they are unrelated to Penokean-aged orogenic events. The ECVC pegmatites are highly fractionated, garnet bearing, and contain a high concentration U, Th, La, Ce, and other rare earth elements. Based on major and trace element associations, the pegmatites in the ECVC are classified as NYF family pegmatites that contain Nb>Ta, REE, U, Th, Zr and are A- to I- types with peralkaline relationship (Cerny and Ercit, 2005).

This study collected bedrock samples from several locations across the ECVC (Little Falls, North Fork, Muskeg Creek) (Figure 1). The pegmatite dikes can range in size from a few meters to 100 m in width near the North Fork of the Eau Claire River. They mainly intrude foliated and metamorphosed Paleoproterozoic to Archean tonalites, amphibolites, and gneisses. Samples from these pegmatites were analyzed for whole rock and mineral chemistries. Whole rock chemistry was analyzed on XRF and ICPMS whereas mineral chemistry was determined using SEM-EDS.

All three locations have quartz, feldspar, plagioclase, biotite, and muscovite. The main mineralogy of Little Falls samples are albite and muscovite. Trace mineralogy of the Little Falls samples include Fe- and Mn-garnet, samarskite, columbite, zircon, and xenotime. Muskeg Creek samples contains both orthoclase and albite with biotite instead of muscovite. Trace mineralogy of the Muskeg Creek samples includes xenotime, monazite, and barite. The North Fork samples mainly contain albite with minor orthoclase and biotite. Trace mineralogy of the pegmatites in the North Fork area include in Fe- and Mn-garnets, monazite, xenotime, and thorite.

The pegmatites from the ECVC are all low in Ca and have trace minerals with rare earth elements. They all contain with albite with low quantities of orthoclase and almost no anorthite. The North Fork and Muskeg Creek samples have more barium-rich minerals than Little Falls, which may be the result of fractionation of feldspars and plagioclase (Yu et al, 2007). Ba-rich minerals can also be a product of hydrothermal activity (Hanor, 2000), but there is no evidence of syn- to post-hydrothermal alteration of the pegmatites. Mn-rich garnets at Little Falls and North Fork indicate a higher degree of fractionation relative to Fe-garnets at Muskeg Creek (Hernández-Filiberto et al, 2021). North Fork and Muskeg Creek also had the largest crystals reaching over 20 cm in size. The North Fork is enriched in the heavy rare earth elements, U, and Th. In comparison, Little Falls has more light rare earth elements. Muskeg is also enriched in light rare earth elements in addition to an increased enrichment of heavy rare earth minerals like Gd and Dy. All three locations contain other metals such as Nb, Zr, Hf.



**Figure 1.** Bedrock geologic map of the Eau Claire Volcanic Complex with site locations. North Fork depicts a pink pegmatite intruding into a grey tonalite. Muskeg Creek depicts a 6 m pegmatite dike with zoning. Little Falls shows a 13 m pegmatite dike. Map from Mudrey & Brown (1982).

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## Revisiting Gravity and Magnetic Anomalies of the Baraboo Range

**HINZE, William J.<sup>1</sup> and LONGACRE, Mark B.<sup>2</sup>**

<sup>1</sup>*Purdue University, 30 Brook Hollow Ln., West Lafayette, IN 47906*

<sup>2</sup>*MBL, Inc., 51 Captain Perry Dr., Phippsburg, ME 04562*

The efficacy of gravity and magnetic methods of geological exploration have increased greatly since they were first used to investigate the Baraboo Synclinorium of Wisconsin nearly 75 years ago (Ostenso, 1953; Hinze, 1959). These methods and their associated technology are used for the first time since then to investigate the geology of the Mesoproterozoic Baraboo Synclinorium, its regional basement, and to illustrate the importance of modern data sets and analysis and interpretation methods. The latter are the result of computers for analysis, interpretation, and presentation of anomalies that were unavailable when the geophysical methods were first applied to mapping the Synclinorium. Analysis and interpretation of current gravity and magnetic anomaly data sets (Figure 1) indicate that the negative gravity anomaly associated with the Baraboo Synclinorium is not unique to the Synclinorium but is the southern termination of the Wisconsin Gravity Minimum (WGM) that covers a large portion of central Wisconsin including the Wolf River Batholith (WRB). The WGM is derived largely from felsic plutons in the upper crust extending outward from the ~1.5 Ga WRB. The lower density of the plutons compared to the metamorphosed orogenic rocks of the upper crust is the likely source of the negative gravity anomaly. The Synclinorium, located along an east-northeast trending gravity and magnetic lineament within the Yavapai orogenic province, occurs in a syncline of largely felsic volcanic rocks (Figures 2 and 3), the Sauk Syncline, that was likely deformed along with the Baraboo Synclinorium by south and southeast-verging thrusting during the Mazatzal and Picuris-Baraboo-Pinware Orogenic events. Variations in thrusting has led to significant differences in the eastern and western portions of the Baraboo Synclinorium.

Key results of the gravity and magnetic anomaly data analysis of the Synclinorium include: (1) The Baraboo Synclinorium's negative gravity anomaly originates in upper crustal Yavapai and Wolf River Batholith felsic plutons that are the source of the Wisconsin Gravity Minimum. (2) The Synclinorium occurs within a synclinal structure resulting from deformation related to generally south-verging, thin-skinned thrust faulting that also produced the Baraboo Synclinorium. (3) The structure of the eastern and western portions of the Baraboo Synclinorium differ likely as a result of variations in the direction and intensity of thrusting during the Mazatzal and Picuris-Baraboo-Pinware Orogenies (~1.63-1.41 Ga).

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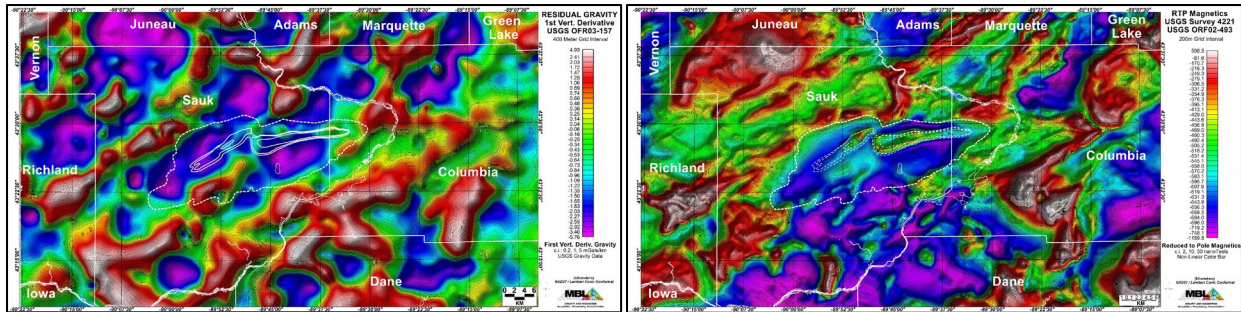


Figure 1. Gravity and magnetic anomaly maps of the Baraboo Synclinorium. Reduced to pole (RTP) total magnetic intensity anomaly map (right) eliminates the effect of the inclined earth's magnetic field on the induced magnetization of the crustal rocks and the vertical gradient Bouguer gravity anomaly map of the Baraboo Synclinorium region (left) minimizes the regional gravity anomaly. The boundaries of the counties are indicated and the outline of the boundary of the Baraboo Synclinorium is the dashed white line. The white line interior to the Synclinorium is the boundary of the Freedom Formation. Color coding of both figures is non-linear.

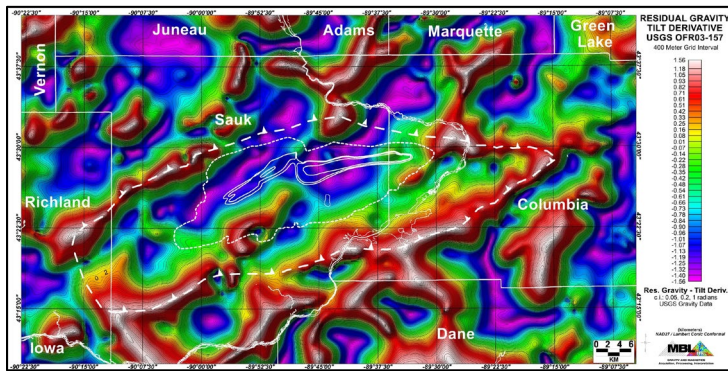


Figure 2. Tilt derivative of the Bouguer gravity anomaly map of the Baraboo Synclinorium region showing the outline of the Sauk Syncline in thick dashed white lines interpreted from the gravity and magnetic anomaly maps. The outline of the Baraboo Synclinorium is the thin dashed white line. The white line interior to the Synclinorium is the boundary of the Freedom Formation. Color coding is non-linear.

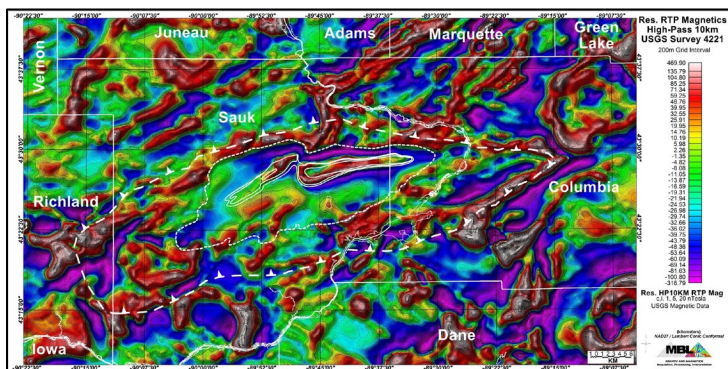


Figure 3. High pass 10-km RTP magnetic anomaly map of the Baraboo Synclinorium region showing the outline of the Sauk Syncline in thick dashed white line interpreted from the gravity and magnetic anomaly maps. The outline of the Baraboo Synclinorium is the thin dashed white line. The white line interior to the Synclinorium is the boundary of the Freedom Formation. Color coding is non-linear.

## Emplacement of the Mesoproterozoic Wausau Syenite Complex, Wisconsin HULA, Linsey<sup>1</sup> and CZECK, Dyanna<sup>1</sup>

<sup>1</sup>Department of Geosciences, University of Wisconsin Milwaukee, Lapham Hall, Room 366,  
3209 N. Maryland Ave. Milwaukee, WI 53211

The Wausau Syenite Complex (WSC) in Marathon County, Wisconsin is an intrusive complex of granitoids emplaced approximately 1.5 Ga (Dewane and Van Schmus, 2007). It is traditionally considered part of a major anorogenic ferroan granite magmatic event that affected the southern margin of Laurentia circa 1.4 Ga. Recent studies have recognized a Laurentian-scale accretionary margin between 1520-1340 Ma (Fig. 1), including the Pinware Orogeny in the northeast, the Picuris Orogeny in the southwest, and the most recently attributed section, the Baraboo Orogeny centered in Wisconsin (Daniel et al., 2023). This new hypothesis provides intriguing opportunities to reconsider the origin and tectonic setting of WSC emplacement as well as other Mesoproterozoic granitoids in Wisconsin, including the larger 1.4 Ga Wolf River Batholith (Dewane and Van Schmus, 2007). This research project will use the orientation of magnetic fabrics within the WSC to better understand how the batholith was emplaced.

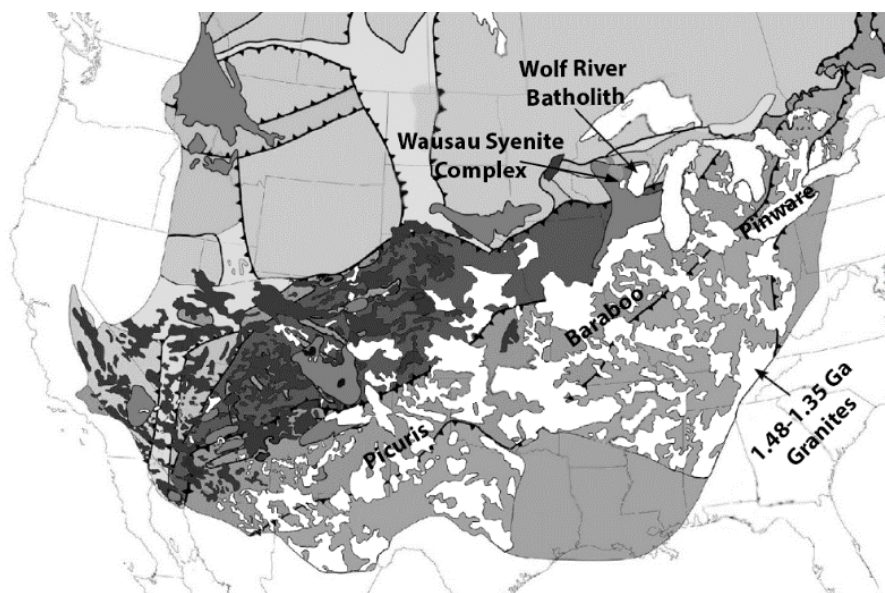


*Figure 1: Simplified geologic map of Precambrian crustal provinces including the Mesoproterozoic accretionary margin of the Picuris, Baraboo, and Pinware Orogenies. The 1.48-1.35 Ga ferroan granites, including the Wolf River Batholith, are highlighted in white and the ~1.5 Ga Wausau Syenite Complex is added. Modified from Medaris et al., 2021, originally based on (Whitmeyer and Karlstrom, 2007).*

The project will consist of an anisotropy of magnetic susceptibility (AMS) survey and thin section analysis of each granitoid within the WSC. With these data, the magmatic flow directions and any subsequent tectonic overprint can be determined, which can be used to constrain the location of the magmatic feeder and the tectonic environment of emplacement. For the purpose of this abstract, three possible outcomes are proposed:

1. Radial magmatic fabrics are preserved, indicating that the WSC was emplaced and cooled prior to the Baraboo Orogeny, with deformation accommodated by the surrounding weaker country rock (Fig. 2A).
2. Magmatic fabrics show a preferential flow pattern parallel to the tectonic margin caused by differential stress from the Baraboo Orogeny, suggesting syntectonic emplacement (Fig. 2B).
3. Only solid-state deformation fabrics are present, implying that the WSC was emplaced before or at the onset of the Baraboo Orogeny and had fully cooled before significant deformation occurred (Fig. 2C).

By focusing on these oldest known Mesoproterozoic ferroan granites in the region, we can learn about the timing and geometry of the earliest Baraboo orogenesis. This study will address the question of how these enigmatic granites fit into the overall tectonic history of the Great Lakes Region.

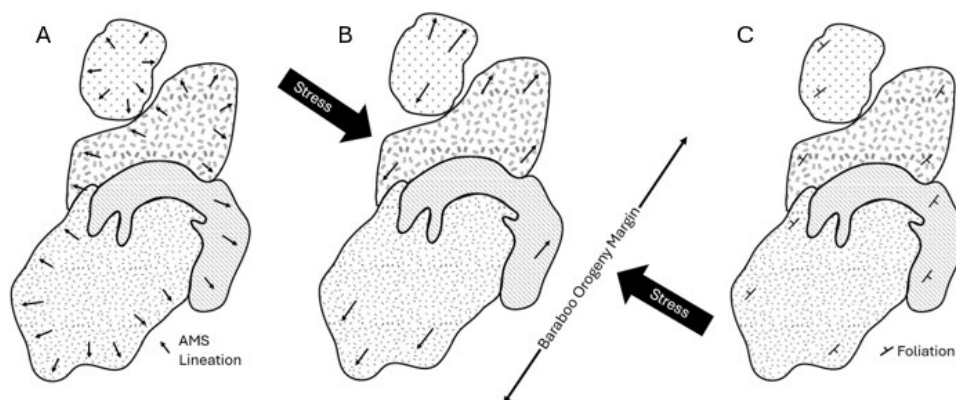


*Figure 1: Schematic diagram of the WSC showing three possible outcomes of the AMS study. A) Radial magmatic fabric. B) Magmatic fabric with preferential flow parallel to the tectonic boundary. C) Solid state fabric.*

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## Mapping oxidation reactions in iron-rich rocks from northeast Minnesota, USA.

JAROZEWSKI, Sarah<sup>1</sup>, DUFFY, Paige<sup>1</sup>, BARRE, Cole<sup>1</sup>, BRENGMAN<sup>1</sup>, Latisha, EYSTER<sup>2</sup>, Athena

<sup>1</sup>*Department of Earth and Environmental Sciences, University of Minnesota Duluth, Heller Hall, 1114 Kirby Drive, Duluth, MN 55812, USA*

<sup>2</sup>*Department of Earth and Climate Sciences, Tufts University, Lane Hall, 2 North Hill Road, Medford, MA 02155, USA*

Aqueous alteration and post-depositional mineral assemblage modification in Precambrian terranes are ubiquitous, but clear accounting of the relative timing of oxidation reactions at the landscape scale is limited. Here we synthesize observations of oxidation and hydration reactions in three iron-rich lithologies in northeast Minnesota, the Soudan Iron Formation, the Cuyuna Iron Formation, and the Partridge River Intrusion of the Duluth complex to contribute to building a compiled relative mineral redox history for the landscape.

The Soudan Iron Formation (~2.7 Ga) is a greenstone-hosted metamorphosed chemical sedimentary unit primarily composed of alternating bands of magnetite, hematite and microquartz affected by at least two Archean deformation events, and later fluid alteration (Thompson, 2015). The Soudan Iron Formation primarily consists of mm-scale bands of authigenic microquartz and iron oxides that preserve in outcrop samples distal to the ore zone, and within the ore horizon at Soudan underground mine. Reflected light petrography of oxides in outcrop samples reveals magnetite replacement by hematite (Figure 1A). Within ore zone samples, complete hematite replacement and large platy hematite is common, similar to previous observations (Thompson, 2015). Clear metamorphic minerals that could indicate high temperatures, pressures, and P-T-path histories are absent from the unit. The younger Cuyuna Iron Formation (~1.9 Ga) is part of an intensely folded metamorphosed sedimentary sequence deformed during the Penokean orogeny (Schmidt, R.G., 1963). Combining new observations and previous data from historic samples (Melcher et al., 1996), oxidation of magnetite is prevalent but limited in samples from the Gloria drill hole (Figure 1B). Metamorphic stilpnomelane is common in the Cuyuna iron formation in contrast to the Soudan Iron Formation. Documented differences in metamorphic silicate mineralogy between these two iron formations may indicate key differences in precursor phases, as both units were affected by significant metamorphic deformation events. Yet, for both, oxidation of magnetite and replacement by hematite indicate both iron formations are similarly affected by post-depositional fluid alteration and oxidation.

The Partridge River Intrusion (PRI) is part of the layered series troctolitic intrusions that form the base of the Duluth complex (Tyson and Chang, 1984). In its present geometry, the magmatic layered series PRI now intersects the current land surface. Clear evidence of aqueous alteration in the first few hundred feet of drill core 17700 includes mineral transformation of biotite and olivine to hydrous ferric oxides and secondary iron silicates (Figure 1C). These replacement reactions are limited in scale, and primary igneous mineralogy is still preserved. Leveraging cross-temporal comparisons of current iron-rich bedrock outcrop exposures and drill cores in north-east Minnesota to identify formational vs. post-formational mineralogy will allow for landscape-scale mapping of oxidation reactions and their extent in the subsurface.

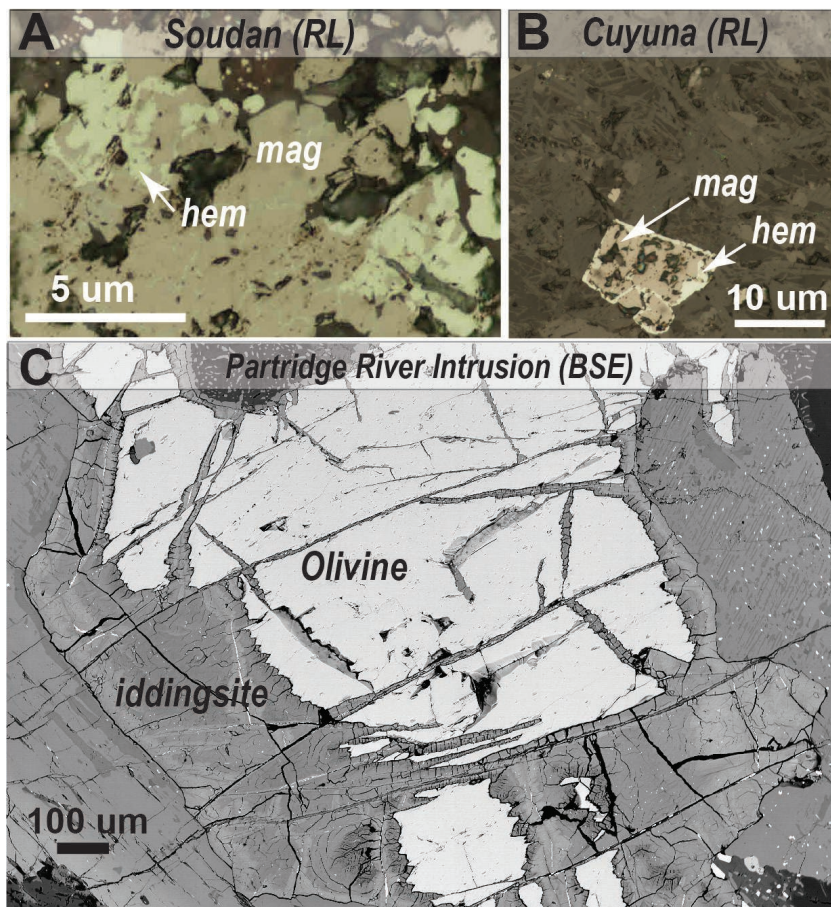


*Figure 1. Reflected light photomicrographs of the Soudan iron formation, Cuyuna Iron formation and back-scatter electron image (BSE) of the Partridge River Intrusion of the Duluth complex. (A) Magnetite is partially replaced by hematite in the Soudan iron formation. (B) Magnetite oxidation to hematite in the Cuyuna iron formation. (C) Back-scatter electron image of altered olivine in the Partridge River Intrusion from the UM-TC EPMA lab, CHARFAC facility..*

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## **Geology and Geochemistry of the Mesoproterozoic Round Lake Intrusion and associated Ti-Mineralization, Northern Wisconsin**

**JEUTTER, Renee O.<sup>1</sup>, LODGE, Robert W.D.<sup>1</sup>**

<sup>1</sup>*Department of Geology & Environmental Science, University of Wisconsin-Eau Claire, 105 Garfield Avenue, Eau Claire, WI 54701, USA*

Modern technology and renewable energy require large amounts of metals that are currently imported, and there is a tremendous effort to domesticate our mineral extraction and processing. Several of these critical minerals, such as Ti, are found in Wisconsin, but little data is available to guide future mineral exploration efforts. The Mesoproterozoic Mid-Continent Rift and its satellite intrusions are known to host Ti-Fe oxide mineralization and Ni-Cu-PGE magmatic sulfide deposits (Woodruff, 2020). During the development of the Mid-Continent Rift, there is a temporal evolution of occurrences of mineral deposits. The plateau stage typically created Ni-Cu-PGE sulfide deposits, layered Ti-Fe oxide deposits, and alkalic hosted U-Nb deposits. The Round Lake Intrusion, like other intrusions discovered through a strong aeromagnetic anomaly (Mudrey et al. 2003), is an example of a layered Ti-Fe oxide deposit. Anorthosite layers alternate with magnetite troctolite layers approximately every 100 ft. Fractional crystallization throughout the evolution of the magma created the alternating “layers” of plagioclase rich and plagioclase poor segments but has minimal additional differences in mineral composition and presence (Stuhr, 1976).

This study describes the petrology and geochemistry of the Round Lake intrusion and Ti-mineralization using historic drill cores stored at the Wisconsin Geological and Natural History Survey core repository. Two holes were relogged, totaling ~1787 feet, and representative samples were obtained of host intrusive phases and mineralization types. The intrusion was characterized via transmitted-light petrography and whole rock geochemistry was determined via WD-XRF. Mineral chemistry of the intrusion and mineralization was determined using SED-EDS. The intrusion segregated into layers: anorthosite, upper magnetite troctolite, middle magnetite troctolite, magnetite, and lower magnetite troctolite, crosscut by an intrusive gabbro dike (Stuhr, 1976).

The main intrusion hosting mineralization magnetite-ilmenite rich troctolite, ranging from 35-60% intergrown magnetite-ilmenite and 5-20% coarse grained plagioclase laths (Figure 1). Movement and flow of magmas during emplacement are indicated trachytic flow textures of aligned plagioclase crystals. The anorthosite has 55-90% euhedral plagioclase, 10-15% magnetite, and 5-15% clinopyroxene. The magnetite-ilmenite rich troctolite and anorthosite are crosscut by fine-grained gabbroic dikes. Within the magnetite-ilmenite troctolite unit, magnetite-titanomagnetite and lesser ilmenite assumes interstitial growth between silicates (Figure 1). Apatite is variably present. Olivine is variably altered to iddingsite and serpentine strips of magnetite forming within fractures in the crystal.

Both the Round Lake intrusion and Clam Lake intrusion are intrusions rich in magnetite associated with the Mid-Continent Rift, and both are likely to be hosts of Ti-Fe ± V deposits and are known to contain large amounts of titanomagnetite with approximately 1.5% V (Woodruff, 2020). Future work is recommended on the Round Lake Intrusion and Ti-mineralization to better constrain the layering and economic potential of Ti-mineralization.

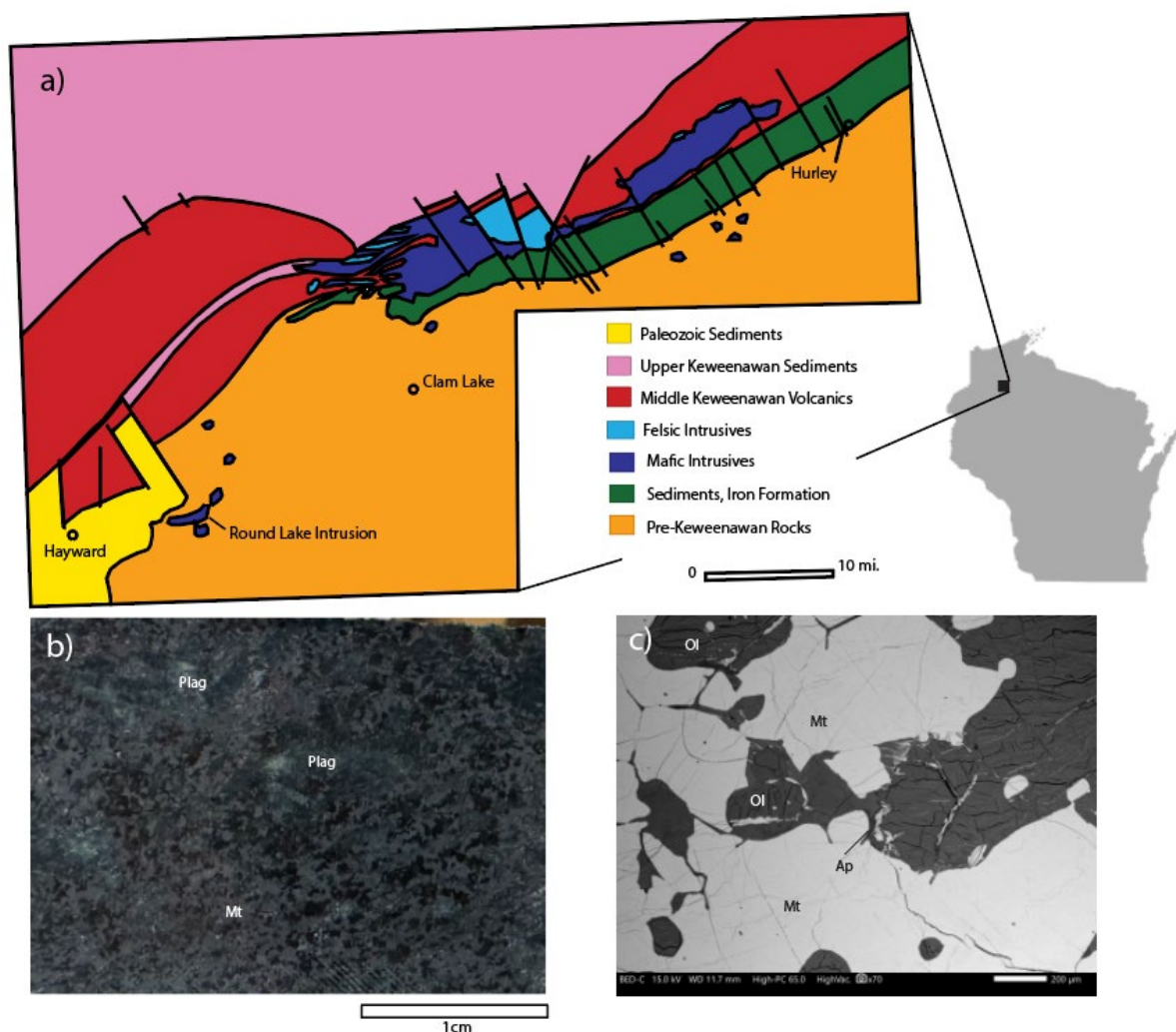


**Figure 1:** (A) Geologic map of Northwestern Wisconsin region surrounding the Round Lake Intrusion, Digitized from Stuhr (1976). (B) Image of Magnetite-Ilmenite rich troctolite core sample showing textures and magnetite matrix filling features. (C) Image from SEM showing major magnetite and olivine textures within a sample. Magnetite matrix filling texture and fracture filling within olivine fractures.

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## Geology and Geochemistry of the Ritchie Creek Cu-Zn deposit, North central Wisconsin

JOHANNESSEN, Haley P.<sup>1</sup>, LODGE, Robert W.D.<sup>1</sup>

<sup>1</sup>*Department of Geology and Environmental Sciences, University of Wisconsin-Eau Claire, Eau Claire, WI 54701 USA*

The Ritchie Creek deposit is a Volcanogenic Massive Sulfide (VMS) deposit located within the Paleoproterozoic Penokean Volcanic Belt (PVB) of northcentral Wisconsin (Figure 1). Mineral exploration efforts have demonstrated that the VMS mineralization at this site is concentrated on the western edge of a felsic volcanic center that is interpreted to have formed in a back arc or intra-arc rift environment within bimodal volcanic sequences (DeMatties, 1990). These interpretations were based on physical descriptions of units intersected in drill core and comparisons to other VMS deposits regionally and globally. Like many VMS deposits in the PVB, little research has been done at the Ritchie Creek prospect to link petrogenesis with larger-scale VMS environments.

This research aims to characterize and refine the geological and geochemical characteristics of the Ritchie Creek Cu-Zn deposit by re-examining historic drill core and representative volcanic stratigraphic units and provide a more comprehensive understanding of the tectonic environment that influenced mineralization. The study involved logging 1,000 linear feet of historic drill core from two holes and collecting 22 core samples from representative stratigraphic units for petrographic and geochemical characterization. The four sampled units include: (1) a medium grey, fine grained quartz mica schist with alternating coarse-grained quartz and K-feldspar bands and disseminated sulfides including pyrite and chalcopyrite, (2) a light green quartz mica schist, strongly altered by sericite and chlorite, containing disseminated chalcopyrite and pyrite, (3) an intermediate metafelsite unit, characterized by sericite and biotite, that grades into a rhyolitic tuff with angular felsic fragments, localized sulfide blebs, and quartz veins, and (4) a semi-massive to massive sulfide unit consists mainly of pyrite with minor chalcopyrite, in a sheared and brecciated matrix.

Major and trace element geochemical data was generated via WD-XRF at the Material Science Center at the University of Wisconsin-Eau Claire. Major element geochemistry is highly variable because of varying degrees of hydrothermal alteration. Therefore, immobile trace elements are used to classify protoliths and discriminate tectonic settings. Least-altered volcanic strata were chemically classified as mafic volcanics (based on low Zr/Ti, high Cr), intermediate volcanics (based on elevated Zr/Ti), and felsic volcanics (based on high Zr/Ti). Mafic volcanic strata have high Zr, consistent with calc-alkalic magmatic affinities. Felsic volcanic strata are F-II type felsic magmas and have low Nb and Y consistent with volcanic-arc felsic magmas. The quartz-sericite altered rocks have trace element chemistry consistent with the intermediate volcanic strata and alteration indices indicate a potassic-dominated alteration. These characteristics suggest an oceanic arc-backarc bimodal-mafic petrochemical association (Piercey, 2011) and provide a more comprehensive understanding of VMS mineralization in the PVB.

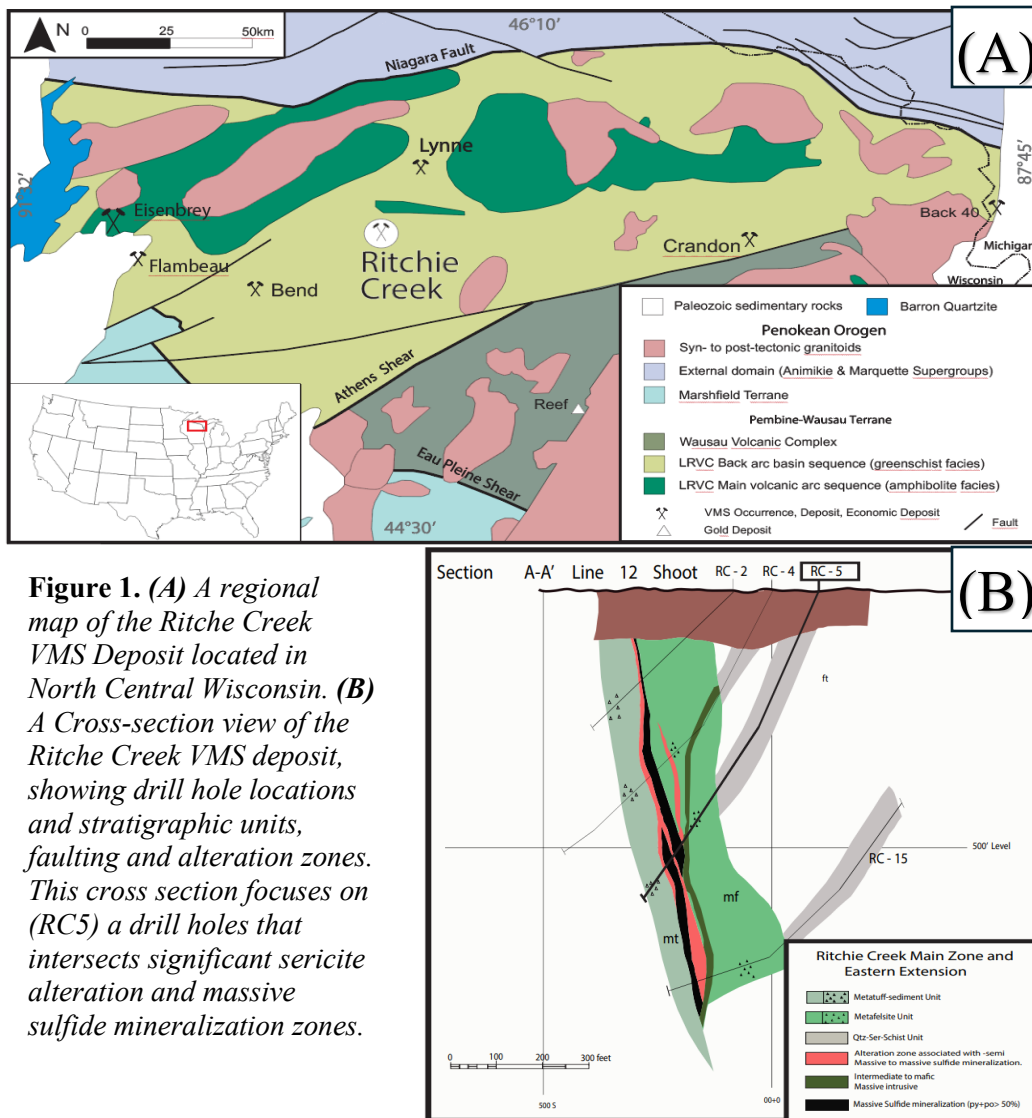


**Figure 1. (A)** A regional map of the Ritchie Creek VMS Deposit located in North Central Wisconsin. **(B)** A Cross-section view of the Ritchie Creek VMS deposit, showing drill hole locations and stratigraphic units, faulting and alteration zones. This cross section focuses on (RC5) a drill holes that intersects significant sericite alteration and massive sulfide mineralization zones.

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**Geologic implications of detrital zircon U-Pb ages from Archean and Paleoproterozoic strata in central Minnesota and the Gogebic Range of Wisconsin and Michigan, USA**  
**JONES, James V.<sup>1</sup>, SALERNO, Ross<sup>2</sup>, CANNON, William F.<sup>2</sup>, and O'SULLIVAN, Paul<sup>4</sup>**

<sup>1</sup> U.S. Geological Survey, Anchorage, AK 99508, USA [jvjones@usgs.gov](mailto:jvjones@usgs.gov)

<sup>2</sup> U.S. Geological Survey, Reston, VA 20192, USA; <sup>3</sup> U.S. Geological Survey, Denver, CO 80225, USA

<sup>4</sup> GeoSep Services LLC, Moscow, ID 83843, USA

Archean and Paleoproterozoic metasedimentary successions in the Lake Superior region of the northern United States record the assembly and breakup of southern Superia and the subsequent transition to long-lived accretionary orogenesis along the southern Laurentia margin. The successions are difficult to correlate for reasons that include contrasts in thickness, facies, and variable amounts of erosion, similarities in depositional environment through hundreds of millions of years of sedimentation, and variable overprinting by younger tectonic events. Detrital zircon U-Pb geochronology is useful for correlating siliciclastic strata and for identifying provenance patterns that reflect past tectonic and sedimentary interactions. We present new data for samples collected from ca. 2.6–1.8 Ga strata from across the Lake Superior region that provide key insights into regional correlations and local to global tectonic histories.

In the eastern Gogebic Range of Michigan, Archean volcanic and volcanoclastic rocks are mapped in a fault-bounded panel between the Watersmeet gneiss dome to the southeast and Neoarchean Puritan batholith to the northwest. One new sample of Archean metagraywacke from within the supracrustal succession yielded only Neoarchean detrital zircon with age populations ranging from ca. 2740 to 2590 Ma, indicating derivation from nearby gneisses but not from older sources such as the early Paleoproterozoic Watersmeet gneiss. A younger succession of Paleoproterozoic metavolcanic and metasedimentary rocks near Lake Gogebic overlies the Archean gneisses and supracrustal rocks. One sample of fine- to medium-grained slate and metagraywacke from the Copps Formation yielded a mixture of Archean and Paleoproterozoic detrital zircon dates. Archean grains were minor and included age populations of ca. 2649 and 2553 Ma that match the nearby Neoarchean metagraywacke and gneiss domains. Paleoproterozoic grains defined a ca. 1846 Ma age peak and a maximum depositional age of ca. 1829 Ma. We also collected samples of the Paleoproterozoic Palms and Tyler Formations that overlie Archean domains in the western part of the Gogebic Range. Fine-grained gray quartzite of the Palms Formation yielded detrital zircon age populations ranging from ca. 2976 to 2458 Ma and a prominent peak at ca. 2675 Ma. The age spectrum indicates input and (or) recycling of Archean sources and an absence of coeval magmatic sources in the region. In contrast, fine-grained argillaceous sandstone of the overlying Tyler Formation contained mostly Paleoproterozoic detrital zircon with major age peaks at ca. 1863 and 1827 Ma together with minor older age populations ranging from ca. 2780 to 1953 Ma.

In central Minnesota, new samples were collected from the Paleoproterozoic Denham and Little Falls Formations. The Denham Formation sample was collected on the northern side of the McGrath gneiss dome and consisted of fine-grained biotite argillite with 1-2 mm horizons of coarser sandstone. The sample yielded chiefly Archean detrital zircon with a dominant age population at ca. 2603 Ma and minor older populations ranging from ca. 3409 and 2789 Ma. Archean age populations match previously published data from nearby samples of basal arkose and dolomitic arkose from the same unit (Craddock et al., 2013). However, that basal arkose also contained a distinct ca. 2101 Ma age population that established a potential correlation between the Denham Formation and the East Branch Arkose of the Dickinson Group in Michigan. The

Little Falls Formation sample of garnet-staurolite-biotite schist was collected from the southern side of the McGrath dome, and it predominately contained Paleoproterozoic detrital zircon that define a dominant unimodal age population at ca. 1846 Ma. The age spectrum for the Little Falls sample is nearly identical our data from the Copps Formation and is also like our Tyler Formation data and to previously published data for other parts of the upper Animikie Group.

The marked difference in the proportion of Archean and Paleoproterozoic grains between the Little Falls and Denham Formations suggests a major change in provenance across their contact. The Denham Formation appears to have been derived from the underlying Archean gneiss dome with lesser contribution from older gneisses elsewhere in the region. Circa 2.1 Ga sources are rare in the region but are found locally to the east in Dickinson County, Michigan. The Paleoproterozoic age population that dominates the Little Falls Formation indicates derivation from the Wisconsin magmatic terrane that was approaching from the south (present coordinates) prior to collision that defines the Penokean orogenic cycle in the region. Additionally, our data indicate a maximum depositional age of ca. 1846 Ma for the Little Falls Formation that contrasts with the inferred ca. 2101 Ma age of the underlying Denham Formation reported by Craddock et al. (2013). Published observations suggest a gradational contact between schist of the Little Falls Formation and dolomitic marble of the underlying Denham Formation (Boerboom and Chandler *in* Bauer et al., 2022). Boerboom and Chandler (2022) noted a 1-meter graphitic/carbonaceous argillite at the base of the Little Falls Formation that could represent a hiatus and then a major change in depositional environment above the arkosic conglomerate and dolostone. We previously reported similar geologic and provenance patterns from the Dickinson Group approximately 600 km to the east in Michigan (Jones et al., 2024). In that area, the East Branch Arkose contains a similar distribution of DZ ages: a mixture of Archean detrital zircon and a distinctive ca. 2099 Ma age population interpreted to have been derived from local granitic sources. The overlying Solberg Schist is made up of biotite-staurolite schist that contains prominent ca. 1.86–1.84 Ga age populations together with minor ca 2.5 and 2.3 Ga age populations. More work is needed to better constrain the stratigraphic position of the depositional age and provenance shifts in both successions and to better understand the tectonic setting and significance of the subtle unconformities and pronounced shift in zircon sources. Preliminary observations and data suggest that the two successions are regionally similar but also distinct from surrounding strata. Thus, the Denham and Little Falls Formations may provide a distinctive and unique record of the transition from Superia rifting to Penokean orogenesis.

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## **Zircon Petrochronology of Wisconsin's Volcanogenic Massive Sulfide Deposits, Northcentral Wisconsin**

**KWIATKOWSKI, Aidan O.<sup>1</sup>, LODGE, Robert W.D.<sup>1</sup>**

<sup>1</sup>*Department of Geology and Environmental Sciences, University of Wisconsin-Eau Claire, Eau Claire, WI 54701 USA*

Northern Wisconsin's Paleoproterozoic Penokean Orogen, one of the classic Precambrian orogenic belts in North America, is known to host multiple volcanogenic massive sulfide (VMS) deposits which are important sources of Cu, Zn, Pb, Ag, and Au globally. Despite known large and potentially economic VMS deposits, limited outcrop exposure has hindered detailed reconstructions of the VMS-hosting environment to guide future exploration. Historic U-Pb geochronology indicates that volcanism occurred between 1889-1835 Ma (Sims et al. 1989) with the majority of VMS-hosting strata constrained between 1875-1873 Ma (Quigley 2016). Schultz & Cannon (2007) attribute the main VMS forming event ca. 1875 Ma to extension in a developing back arc basin, with a second later magmatic pulse around 1830 Ma being attributed to post-tectonic stitching plutons. However, a newer model by Zi et al. (2022) shows two VMS forming events around 1875 Ma and 1845 Ma suggesting a regime consisting of alternating compressional and extensional environments caused shifting subduction angles.

Zircon petrochronology (U/Pb, Lu/Hf isotopic data and trace elements) can not only better constrain the timing of VMS formation but can also allow for a more complete understanding of the geological evolution and metallogeny of Wisconsin VMS deposits. This study sampled felsic igneous rocks from several VMS deposits to determine the timing and tectonic settings of VMS environments in the western Penokean Orogen. Samples were studied from the Flambeau, Eisenbrey, and Lynne deposits of the Ladysmith-Rhineland Volcanic Belt (Figure 1a). Samples from the Flambeau and Eisenbrey deposits consist of felsic volcanoclastic units associated with sulfide mineralization and the sample from the Lynne deposits consists of a granodiorite which has intruded into the VMS deposit and volcanic strata. Samples were pulverized and heavy mineral separates were obtained by various magnetic and density separation techniques. The zircon mineral grains were imaged by cathodoluminescence prior to isotopic (U/Pb, Lu-Hf) and trace element analyses via LA-ICPMS at the Mineral Exploration Research Centre at Laurentian University, Sudbury, Ontario. U/Pb isotopic data constrains timing of magmatism. Trace elements and Lu-Hf data constrain the tectonic setting and crustal architecture.

Preliminary results indicate two distinct VMS-forming magmatic events during the Penokean Orogeny that have similar tectonic and magmatic styles. All samples show a bimodal distribution of U/Pb ages centered on 1830-1835 Ma and 1870-1875 Ma (Figure 1). Trace element geochemistry of zircons reveals little petrogenetic difference between the magmatic events. Negative  $\epsilon\text{Hf}_{(t)}$  values, indicating interaction with Archean basement, is consistent amongst all samples and between magmatic events. The VMS-forming extensional event at ca. 1835 Ma contradicts the Schulz and Cannon (2007) model where collisional tectonics are dominant at this time. While the timing of VMS-formation more closely aligns with the Zi et al. (2022) model, the accordion-like tectonics cannot explain the lack of variation in magmatic setting or crustal architecture observed in our data. Therefore, additional data is needed to fully understand the tectonic and metallogenic significance of this younger extensional event.

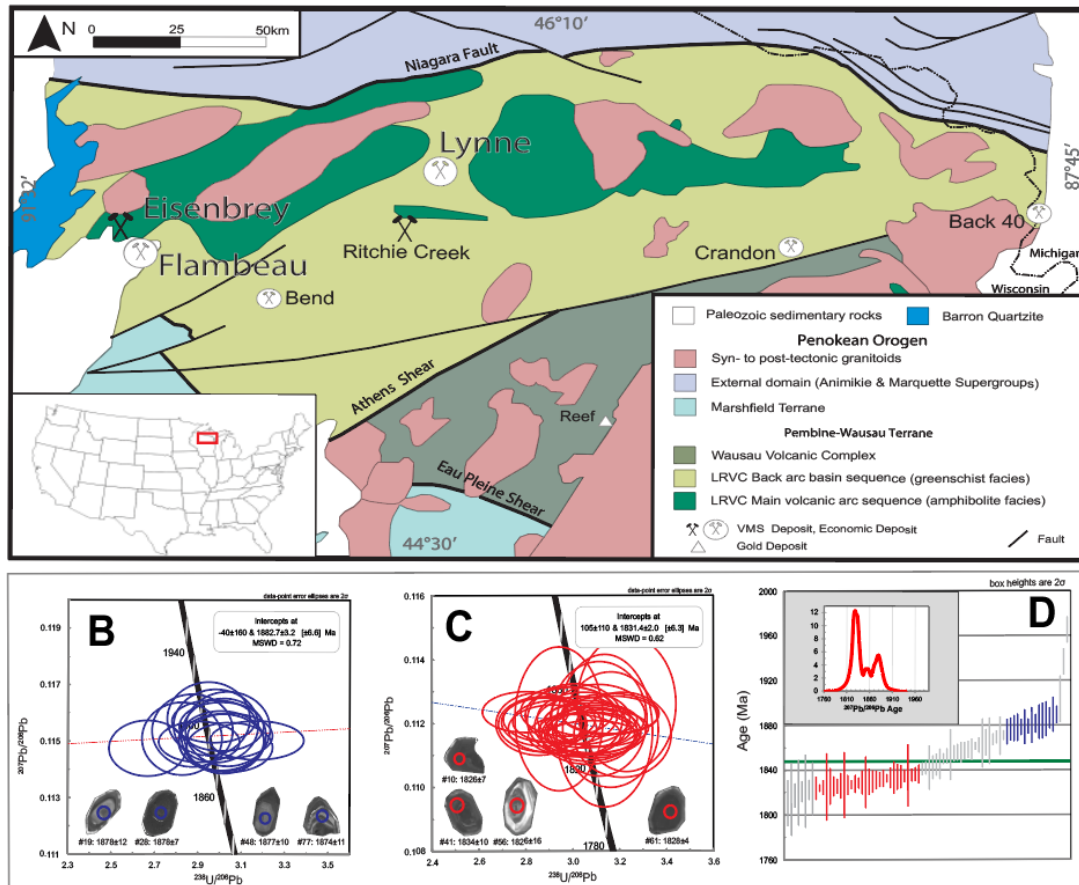


Figure 1. A) Generalized geologic map of the Penokean Orogen illustrating major tectonostratigraphic subdivisions and the location of sampled and major VMS occurrences. Figure modified from Schulz and Cannon (2007) and DeMatties (1994). Subdivisions of Pembine-Wausau terrane from DeMatties (1994, 2018). LRVC = Ladysmith-Rhineland volcanic complex. B) U/Pb concordia diagram of older magmatic zircons. C) U/Pb concordia diagram of younger magmatic zircons interpreted to be crystallization age of sample. D) Weighted mean diagram distribution of ages and analyzed grains. Inset image shows frequency distribution of ages in samples.

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## **Geologic Interpretation of Filtered Gravity and Magnetic Anomalies of the Baraboo Range LONGACRE, Mark B.<sup>1</sup> and HINZE, William J.<sup>2</sup>**

<sup>1</sup>*MBL, Inc., 51 Captain Perry Dr., Phippsburg, ME 04562*

<sup>2</sup>*Purdue University, 30 Brook Hollow Ln., West Lafayette, IN 47907*

Investigations over the past decade have made significant advances in our geologic knowledge of the Mesoproterozoic Baraboo Synclinorium and adjacent region of south-central Wisconsin (e.g., Medaris, Jr. et al., 2021; Stewart et al., 2021; Marshak et al., 2023). To further the geologic information of this feature and nearby region we have filtered their gravity and magnetic anomaly maps to identify geologic formations and structures in the crystalline basement. The filtered maps isolate specific attributes of the anomaly fields which are useful in interpretation especially when combined with constraining geological information. These maps have identified a buried geologic structure to the east of and immediately adjacent to and along strike of the Sauk Syncline (Figures 1 and 2) which encompass the Baraboo Synclinorium. The buried structure is a near mirror image of the Sauk Syncline and thus is referred to as the Twin Syncline. Unlike the Sauk Syncline and the Baraboo Synclinorium the eastern structure is south rather than north of a geological lineament within the Yavapai orogenic province that marks the southern boundary of the Wisconsin Gravity Minimum. The Twin Syncline is notable in the magnetic anomaly map because of the positive anomaly associated with a magnetite-rich formation that is likely an extension of the lower portion of the Freedom Formation of the Baraboo Synclinorium. The elliptical trace of this anomaly and the steep gradients of the outer margin support the synclinal nature of the structure. We interpret this structure to be a result of south-verging thrusting with steeply dipping thrusts along the northern and southern margins of the Twin Syncline similar to the situation of the Sauk Syncline. This structure is not as tightly folded as the Baraboo Synclinorium suggesting that the thrusting to the east of Baraboo Synclinorium was less intense. The Syncline can be identified on the filtered maps as can other quartzite synclinoriums of the region by the subdued geophysical anomalies of the underlying felsic volcanic rocks because of their burial beneath the non-magnetic quartzite. The magnetic anomalies of the magnetic lower half of the Freedom Formation are also a useful marker for detailing the structure within the Baraboo Synclinorium and defining the limits of the Freedom Formation within it. Additionally, two parallel intrusives on strike with the Denzer Diorite that crops out along the southwestern margin of the Synclinorium extend north-northeasterly within the sub-quartzite basement across the western portion of the Synclinorium. They are associated with anticlines within the Synclinorium that may have resulted from differential deformation caused by variations in the rheology of the basement rocks. These and other interpretations of the filtered gravity and magnetic anomalies suggest that revisiting the studies of basement rocks of Wisconsin and adjacent regions is in order using the available improved analysis, interpretation, and presentation methods and modern data gravity and magnetic data sets.

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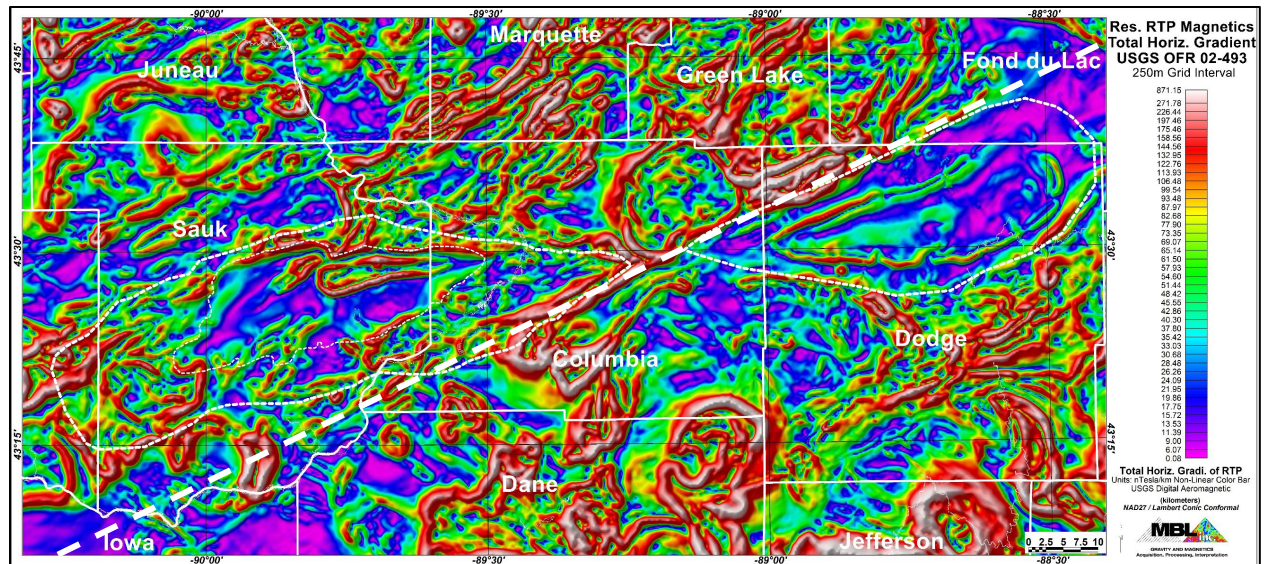


Figure 1. Total horizontal derivative of the RTP total magnetic anomaly map of south-central Wisconsin. The outlines of the Sauk (left) and Twin (right) Synclines are shown by the thin dashed white lines and the Baraboo Synclinorium by a dashed white line. The Baraboo Lineament of the Yavapai province is shown by the wide broadly dashed line. Color coding is non-linear.

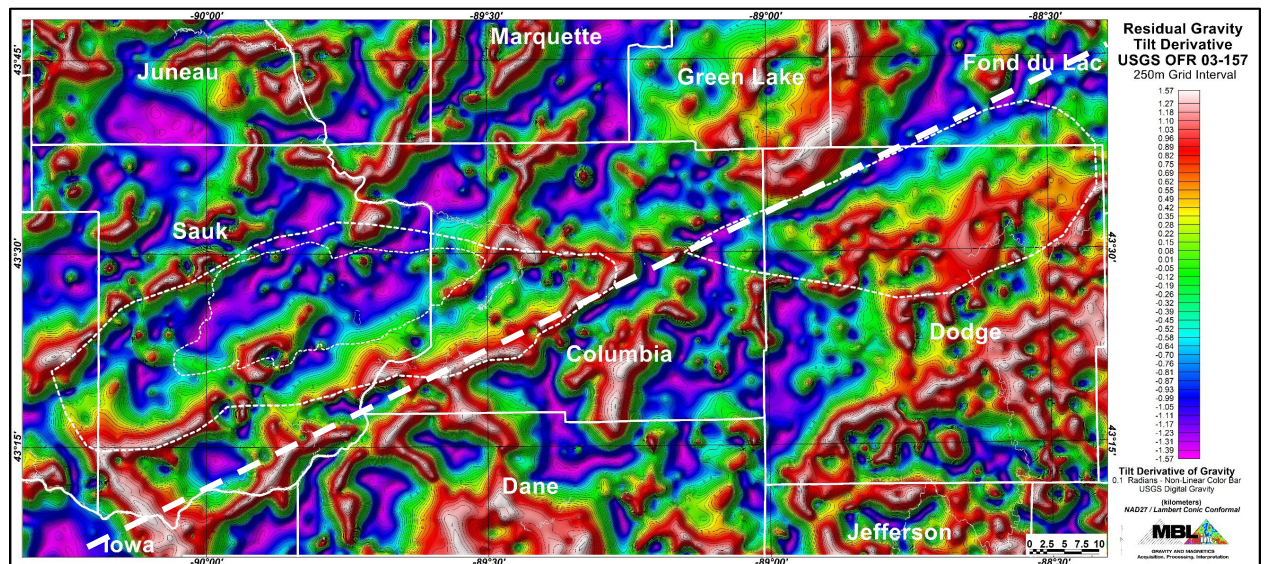


Figure 2. Tilt derivative of the Bouguer gravity anomaly map of south-central Wisconsin that emphasizes the short wavelength components. The outlines of the Sauk (left) and Twin (right) Synclines are shown by the dashed white lines and the Baraboo Synclinorium by a thin dashed white line. The Baraboo Lineament of the Yavapai province is shown by the wide broadly dashed line. Color coding is non-linear.

## **An Informal Review of the ILSG Field Excursion to Hawaii, January – February, 2025**

**MACTAVISH, Allan<sup>1</sup>, HINZ, Peter<sup>1</sup>, HUDAK, George<sup>1</sup>, LARSON, Phil<sup>1</sup>, AUBUT, Allan<sup>1</sup>, BOERBOOM, Terry<sup>1</sup>, CHILTON, Vern<sup>1</sup>, DeGRAFF, Jim<sup>1</sup>, ERICKSON, Tom<sup>1</sup>, FAULKNER, Barb<sup>1</sup>, SERRANO, Isabel<sup>1</sup>, and ZANKO, Larry<sup>1</sup>**

<sup>1</sup> *Members of the 2025 ILSG Field Trip to Hawaii, 2025*

Between January 24, 2025 and February 5, 2025, twelve members of the Institute on Lake Superior Geology participated in a geological field excursion to investigate the geology of the island of Hawaii, with a focus on observing field relationships, outcrop characteristics and geomorphology to better understand the characteristics of modern basaltic volcanism in a hot-spot environment. The field excursion was led by Allan MacTavish, Peter Hinz, George Hudak and Phil Larson. A new field trip guidebook and glossary of geological terms (MacTavish and Hudak, 2024) was prepared and utilized during the thirteen-day long trip.

This presentation will review key features and take-aways from the excursion, which included investigations of five of the seven volcanoes associated with the island of Hawaii. Investigations took place via examinations of various outcrops, hikes through the Hawaiian wilderness, and a helicopter tour. Various eruption types, volcano types, coherent (lava flow) and volcanoclastic deposit types and features, different types of volcanic products and hydrothermal alteration facies, and observations of historical and cultural artifacts and natural phenomena will be discussed. Challenges and surprises associated with field studies of Hawaii will also be presented.

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## **Refining the Age and Occurrence of Basement Rocks in Northwest Iowa: Implications for Precambrian Tectonics and Magmatic Evolution of the Laurentian Midcontinent**

**MALONE, Jack<sup>1</sup>, MALONE, David<sup>2</sup>, ANDERSON, Raymond<sup>1</sup>, CLARK, Ryan<sup>1</sup>**

<sup>1</sup>*Iowa Geological Survey, University of Iowa, Iowa City, IA 52242 USA*

<sup>2</sup>*Geography-Geology, Illinois State University, Normal, Illinois 61790*

Precambrian basement rocks in northwest Iowa reveal an Archean and two Paleoproterozoic tectonic sutures (Figure 1; 1.9-1.8 Ga Trans-Hudson/Penokean and 1.8-1.7 Ga Yavapai; Bickford et al., 1986; Holm et al., 2007). Here we present four new U-Pb (LA-ICPMS) ages for drill cores of basement rocks along the Transcontinental Arch in northwest Iowa, USA (Figure 2). The cores are on repository at the Iowa Geological Survey. The Camp Quest migmatite gneiss was sampled at a depth of 1,078 ft from the Camp Quest D-21 core (W25498; z=38). The weighted mean and Concordia ages were both 1845 Ma, which is the first Trans-Hudson/Penokean age recognized in Iowa. This core is located south of the Spirit Lake tectonic zone (SLTZ) which is interpreted as the suture between Yavapai terrane rocks to the south and Archean Superior province rocks to the north. Nine inherited zircons are mostly Archean in age and interpreted as xenocrysts, indicating Archean crust occurs at depth south of the SLTZ. Granite was also sampled at a depth of 660 ft from the Hawarden D-7 core (W27270; z=35). The zircon age spectrum reveals three age clusters at ~2895, ~2683, and ~1800 Ma. The older, inherited age clusters are consistent with ages of the Minnesota River Valley terrane and the greater Superior Province, respectively. The ~1800 Ma age is similar to the nearby 1803-1810 Ma Matlock “keratophyre” and the distant 1805 Ma Humboldt granite (northern Michigan), representing the initiation of north-directed Yavapai subduction and granitic melt production into Archean and previously accreted Trans-Hudson/Penokean rocks north of the SLTZ (Kilburg, 2024). Granodiorite was sampled at a depth of 915 ft from the Harris D-13 core (W27270; z=41). The weighted mean and Concordia ages are ~1780 Ma, suggesting that Yavapai rocks intrude older Trans-Hudson/Penokean or Archean rocks north of the SLTZ. A late-stage granitic dike was sampled at a depth of 1,611 ft from the Spencer BX-2 core (W16223; z=7), which is from a tabular noritic body within the Spencer intrusive complex just south of the SLTZ. The sampled interval yielded sparse zircons; however, the weighted mean age of 1238 Ma is the first Grenville age recognized in Iowa. This age suggests an obscure early Grenvillian thermal resetting or reactivation in the upper Midcontinent which postdates anorthositic/noritic magnetism concentrated along the SLTZ at Spencer.

New complementary whole rock WDXRF major oxide and ICP-OES trace element geochemical analyses (n=163) from Precambrian units in northwest Iowa reveal a complex tectonic and crustal growth configuration. Intermediate to felsic intrusions are generally LREE-enriched and have I-type volcanic arc-like trace element patterns. The origin of anorthositic to mafic-ultramafic occurrences are less straightforward but are characterized by slight to significant Ce, Sm, Eu, and Lu anomalies, indicating basaltic to mantle fractionation, differential partial melting at depth, and/or derivation from Fe-rich residual melts. These new results provide significant insight into the tectonomagmatic evolution of the southernmost Superior Province during the final assembly of the Laurentian craton.

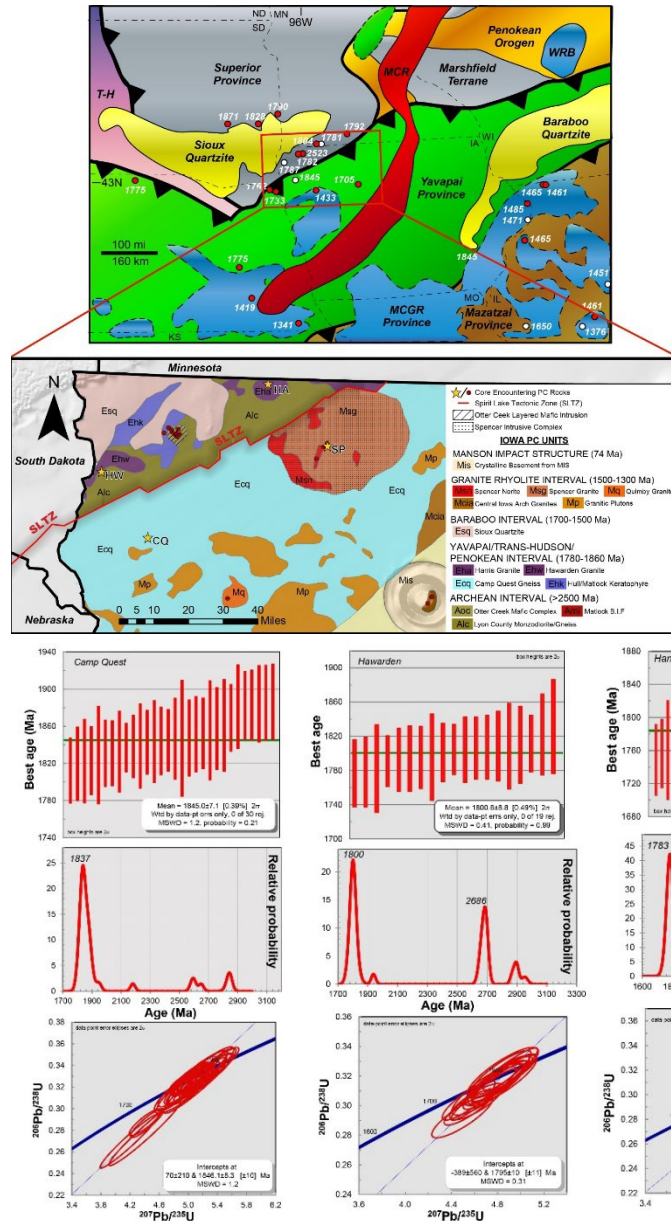


Figure 1: Geological map of Precambrian basement rocks in the northern midcontinent and northwest Iowa. Top: Red dots indicate previously published U-Pb ages and white dots are new (this study). Bottom: New geochronologic ages indicated with stars are CQ = Camp Quest, HW = Hawarden, HA = Harris, SP = Spencer.

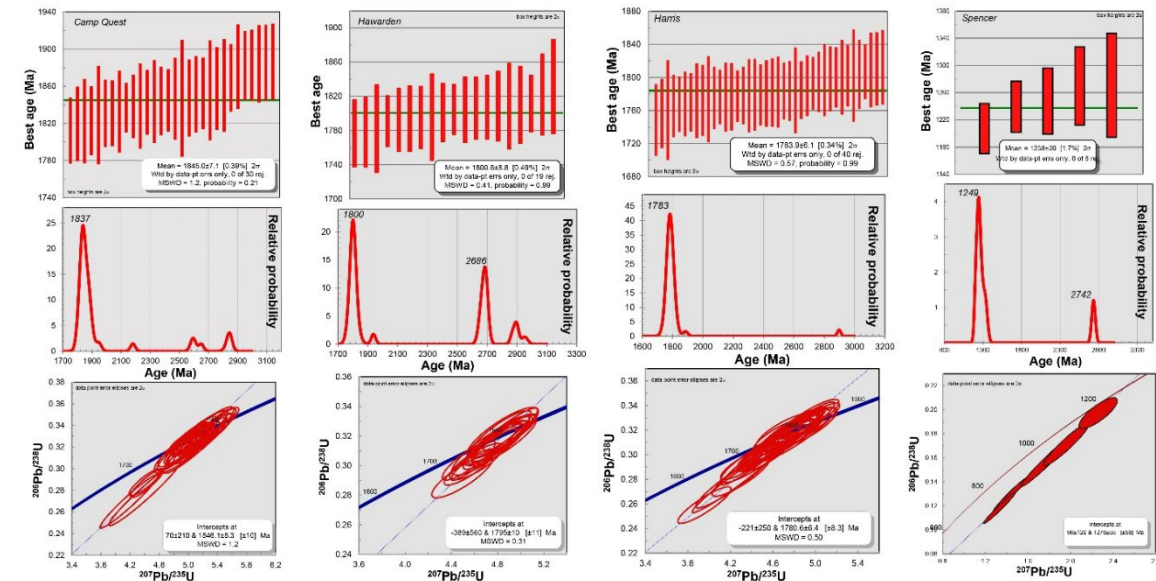


Figure 2: Weighted mean, probability density, and Concordia plots of newly dated Precambrian units in northwest Iowa.

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## Post-Penokean and Pre-Yavapai Magmatism and Sedimentation in Central Wisconsin (Southern Lake Superior Region)

MEDARIS, Gordon Jr.<sup>1</sup> and MALONE, Dave<sup>2</sup>

<sup>1</sup>Dept. of Geoscience, University of Wisconsin-Madison, Madison, WI 53706

<sup>2</sup>Dept. of Geography, Geology, and the Environment, Illinois State University, Normal, IL 61790

The principal Precambrian domains in Wisconsin are the *Penokean Province*, consisting of the Marshfield Terrane, Wausau-Pembine Terrane, and Craton margin, which include 2450-1770 Ma craton margin and foreland basin sediments and 1890-1830 Ma volcanic arc associations, 1760 Ma rhyolite and granite of the *Yavapai Province*,  $\leq 1643$  Ma quartzite of the *Baraboo Interval*, 1484-1468 Ma granitic rocks of the *Wolf River batholith*, and 1109-960 Ma igneous and sedimentary rocks of the *Midcontinent Rift* (Fig. 1).

In addition to these five major domains, small outcrops of post-Penokean and pre-Yavapai igneous and sedimentary rocks are scattered across central Wisconsin, which have been investigated in detail at Hamilton Mounds (Medaris et al., 2007), Biron Dam (Holm et al., 2020), and Brokaw (this report) (Fig. 1).

Two sedimentary successions occur at *Hamilton Mounds*: an older arkose and a younger quartzite correlative with the Baraboo quartzite. The arkose is a gray, fine- to medium-grained, feldspathic sandstone (CIA = 59.0; Fig. 2). Detrital monazite in arkose yields a total Pb median age of 1850 Ma, with the youngest detrital grain at 1757 Ma, signifying post-Penokean deposition of the arkose. An upper age for the arkose is provided by the intrusion of  $1762 \pm 7$  Ma granite (Yavapai), whose age is within error of the youngest detrital monazite grain. Muscovite in the younger quartzite yields a  $^{40}\text{Ar}/^{39}\text{Ar}$  plateau age of  $1470 \pm 11$  Ma, reflecting the widespread thermal effect of the Wolf River batholith throughout central and southern Wisconsin.

At *Biron Dam*, trachybasaltic diabase dikes (Fig. 2) intruded Archean gneiss and Penokean tonalite, granodiorite, and granite. Zircon grains in three samples of diabase yield  $^{207}\text{Pb}/^{206}\text{Pb}$  ages within error of each other, with a weighted mean age of  $1817 \pm 2$  Ma, which demonstrates post-Penokean and pre-Yavapai emplacement of the dikes. The diabase dikes have been metamorphosed under amphibolite-facies conditions; hornblende in metadiabase yields a  $^{40}\text{Ar}/^{39}\text{Ar}$  plateau age of  $1672 \pm$  Ma, possibly representing a Mazatzal influence.

At *Brokaw*, polymictic conglomerate, feldspathic sandstone (CIA = 59.0; Fig. 2) and siltstone were intruded by rhyolite, which contains inherited zircon with ages between 2125 Ma and 3565 Ma. The sandstone contains detrital zircon with a  $^{207}\text{Pb}/^{206}\text{Pb}$  median age of 1850 Ma and an age of 1810 Ma for the youngest subset of grains with overlapping errors, demonstrating post-Penokean deposition of the Brokaw sedimentary rocks. Primary structures and textures of the Brokaw igneous and sedimentary rocks have been preserved on the macroscopic scale, but such rocks have been pervasively recrystallized to greenschist-facies mineral assemblages on the microscopic scale, as seen for example in rhyolite, in which plagioclase was replaced by albite and epidote, and hornblende, by epidote (Fig. 3). The age of such recrystallization has not yet been determined, but is presumed to be related to the nearby Wolf river batholith.

It is now recognized that igneous rocks were emplaced and sedimentary rocks were deposited over much of central Wisconsin in the interval 1817-1757 Ma after the Penokean orogeny, perhaps as a precursor to the Yavapai orogeny.

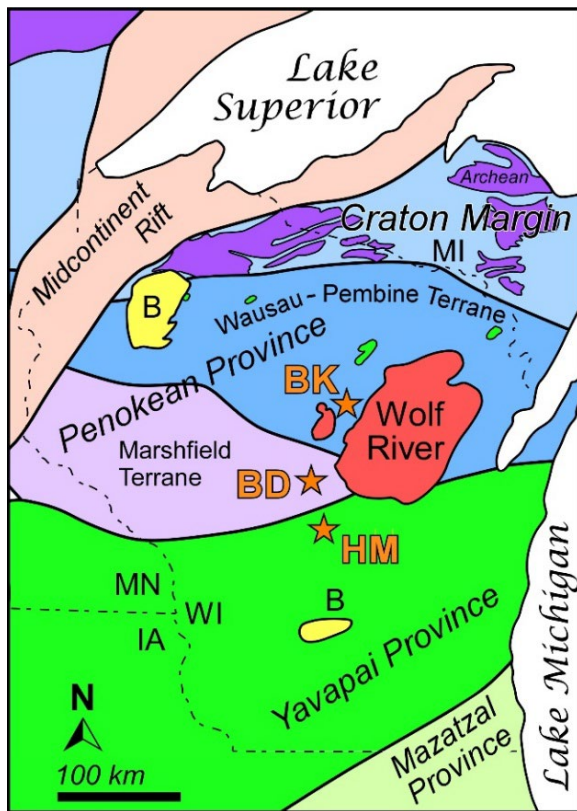


Figure 1. Map of the major Precambrian geological units in the southern Lake Superior region. Star symbols: Brokaw (BK), Biron Dam (BD), and Hamilton Mounds (HM) localities; B: Baraboo Interval sedimentary rocks.

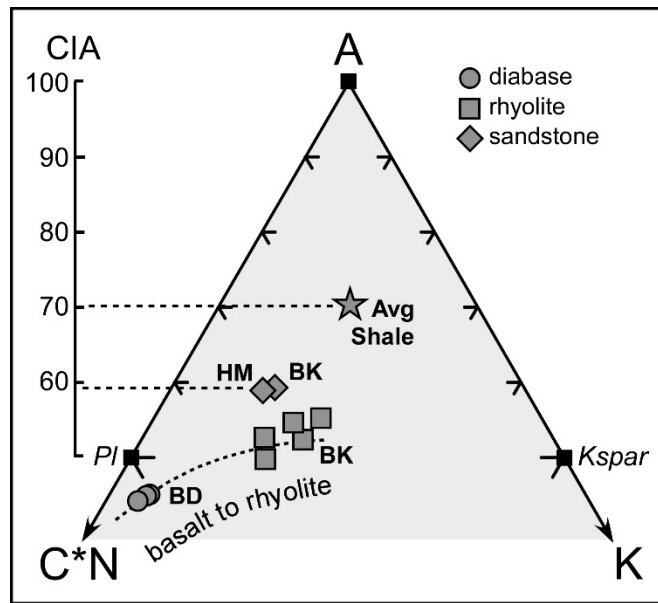


Figure 2. Chemical compositions of Biron Dam diabase, Brokaw rhyolite and sandstone, and Hamilton Mounds sandstone in terms of Al ( $\text{Al}_2\text{O}_3$ ), Ca\* ( $\text{CaO}$ ), N ( $\text{Na}_2\text{O}$ ), and K ( $\text{K}_2\text{O}$ ); CIA: Chemical Index of Alteration.

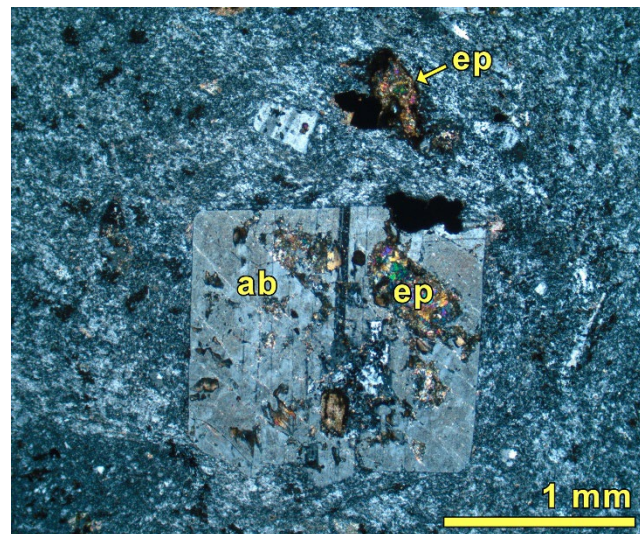


Figure 3. Photomicrograph (crossed polarizers) of recrystallized Brokaw rhyolite; ab, albite; ep, epidote

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## US Steel Corporation / Ralph W. Marsden iron ore collection

**MOOERS, Howard<sup>1</sup>, SEVERSON, Mark<sup>2</sup>, JONGEWAARD, Peter<sup>3</sup>, LARSON, Phillip<sup>4</sup>**

<sup>1</sup>*Department of Earth and Environmental Sciences, University of Minnesota Duluth, Duluth, MN 55812*

<sup>2</sup>*2122 W 22<sup>nd</sup> St., Duluth, MN 55811, USA*

<sup>3</sup>*7009 Three Lake Rd., Canyon, MN 55717, USA*

<sup>4</sup>*1613 14<sup>th</sup> Ave. East, Hibbing, MN 55746, USA*

By the time Ralph W. Marsden joined Oliver Iron Mining Division of US Steel Corporation (USSC) in 1951 he was already one of the World's experts on iron ore. From 1953-1964 he managed the Geologic Investigations Unit in Duluth, MN. During this time, Ralph was one of the co-founders of the Institute on Lake Superior Geology in 1954. In 1964 Ralph was transferred to the Pittsburgh corporate office as Manager of Geologic Investigations, Iron Ore, however, Ralph wanted to return to Minnesota, and in 1967 he left USSC and moved to the University of Minnesota Duluth (UMD) Department of Geology as Professor and Head. USSC had an active, worldwide exploration program for iron ore from the 1920s into the 1960s, and a large number of the samples collected were housed in Duluth, MN. When USSC closed its Duluth, MN, office, this iron ore sample collection was to be discarded. Ralph "rescued" the collection of iron ore samples and moved them to the University of Minnesota Duluth. In 1986, Ralph died suddenly while attending the Geological Society of America Annual Meeting in San Antonio, TX. The collection of iron ore samples sat in a service tunnel at UMD for 40 years. This globally significant collection of iron ore samples was recently inventoried, photographed, and placed in storage containers that are readily accessible. The inventory of the 483 samples, complete with photographs, is cataloged on the University of Minnesota Digital Conservancy (<https://hdl.handle.net/11299/265081>). Many of these samples are from localities that are no longer accessible, are from closed mines, or are from areas of the World that simply cannot be visited because of political and social issues.

This collection of iron ore samples dates from 1926 to the 1960s and has samples from 25 countries and 30 US states and Canadian provinces. The individual sample boxes are labeled, and many have great detail on the origin of the samples. Most of the samples are also individually labeled, with sample numbers and descriptions. There are photographs of the contents of each box, and where possible supporting documents are shown in the photos. For further information or to request access to samples contact the Department of Earth and Environmental Sciences, University of Minnesota Duluth or Howard Mooers ([hmooers@d.umn.edu](mailto:hmooers@d.umn.edu)).



Figure 1. Example of samples from Liberia, West Africa, with supporting documentation.

**Countries represented:** USA, Angola, Australia, Brazil, Canada, Chile, Colombia, Congo, Costa Rica, Cuba, Gabon, Germany, Guatemala, Honduras, India, Ivory Coast, Liberia, Mexico, Nicaragua, Namibia, Portugal, South Africa, Sudan, Sweden, Venezuela.

**US States and Canadian Provinces represented:** Alabama, Alberta, Arizona, British Columbia, California, Idaho, Illinois, Massachusetts, Michigan, Minnesota, Missouri, Montana, Nevada, New Jersey, New Mexico, New York, Newfoundland, North Carolina, North Dakota, Ontario, Oregon, Puerto Rico, Quebec, South Dakota, Utah, Virginia, Washington, Wisconsin, Wyoming.

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## **Lithogeochemical Characterization of Manganese Mineralization at the Cuyuna Range, Central Minnesota**

**PALIEWICZ, Cory<sup>1</sup>, THAKURTA, Joyashish<sup>1</sup>**

*<sup>1</sup>Natural Resources Research Institute (NRRI), University of Minnesota Duluth, 5013 Miller Trunk Hwy, Duluth, MN 55811*

The Paleoproterozoic Cuyuna Range of central Minnesota contains elevated levels of manganese when compared to other Banded Iron Formations in the Lake Superior region. The total tonnage is estimated at 49 million metric tons at 7.84 percent Mn (Kilgore and Thomas, 1982). The Cuyuna Range consists of a Penokean fold-and-thrust belt divided into the Emily District, North Range, and South Range. These are separated by structural and stratigraphic discontinuities which make each area geologically distinct (Southwick et al., 1988; Morey, 1990). Although prior work has documented a variety of textural and sedimentary associations, this study will provide new lithogeochemical data to further characterize the manganese-bearing lithologies across the Cuyuna Range in support of ongoing research for manganese and other critical minerals in Minnesota as part of the USGS Earth MRI program.

A total of 201 drill core samples were collected from 37 drill holes across the Emily District, North Range, South Range, and Glen Lake Sulfide Deposit (Figure 1). To date, all samples have been studied in hand-sample and sent for bulk geochemical analysis, 40 samples have been analyzed in thin section, and whole-rock geochemical results of 60 samples from 16 drill holes have been received from the USGS. Although lithologic features of both iron-formations and non-iron-formations are variable across the range, the deposits also share many attributes. As such, we find it useful to texturally classify the collected samples into granular, banded, and irregular types while still recognizing the special characteristics of each individual mineral association.

This study will present petrographic and whole-rock geochemical data, with particular emphasis on rocks from the Emily District, which from past studies is known to be most-enriched in Mn-content. In addition, Mn-bearing country rocks throughout the Cuyuna Range are also characterized and compared to historic drill logs and prior work (e.g., Morey et al., 1991, Dahl et al., 1992). In this way, new insights on lithological variation, manganese distribution, and other potential critical minerals at the Cuyuna Range may further be addressed and incorporated during the Earth MRI program.

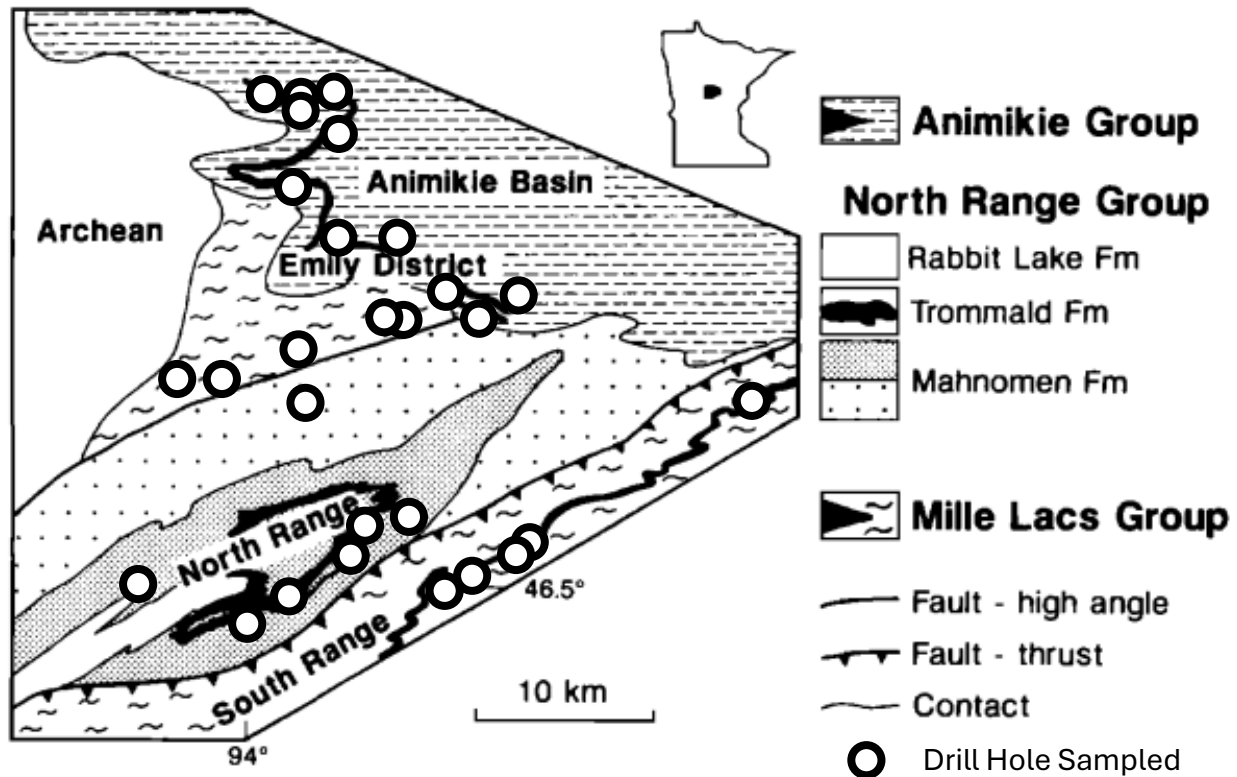


**Figure 1:** Regional geologic map of the Cuyuna Range showing approximate drill hole locations sampled for this study. Modified from Southwick et al., 1988 and Cleland et al., 1996.

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## Michigan Geological Survey's Contributions to the USGS Earth MRI National Mine Waste Inventory Effort

**PEARSON, Sara<sup>1</sup>, GAMET, Nolan<sup>2</sup>, SHALIFOE, Molly<sup>1</sup>, QUIGLEY, Ashley<sup>2</sup>, and MAHIN, Robert<sup>2</sup>**

<sup>1</sup>*Michigan Geological Survey, Western Michigan University, 5272 W. Michigan Ave. Kalamazoo, MI 49009*

<sup>2</sup>*Michigan Geological Survey, Western Michigan University, 416 Avenue C Gwinn, MI 49841*

In the mid-19<sup>th</sup> century, the discovery of rich copper and iron deposits in Michigan's Upper Peninsula (U.P.) led to intense mining, resulting in hundreds of abandoned mine waste sites. Both published and unpublished geological literature suggests that some of these legacy mine waste sites have the potential to host critical minerals, such as manganese and graphite, that were previously overlooked during production. The Michigan Geological Survey (MGS) is contributing to the United States Geological Survey's (USGS) national effort to build a comprehensive national inventory of mine wastes, their compositions, and potential critical minerals.

The MGS team has completed an inventory and submitted 120 mine waste sites from 6 counties across the western U.P. to the USGS for a final review and inclusion in the national mine waste database (Figure 1). These 120 sites are further subdivided into 216 individual mine waste features that met the minimum 2,000m<sup>2</sup> size requirement. Finalized point and polygon layers for each mine site were accompanied by corresponding geology, resource, and reference attribute tables. The process consisted of creating an ArcGIS Pro project, adding all available mine-related state and federal datasets, LiDAR-derived DEMs (digital elevation models), published maps, and an ArcGIS geodatabase template containing feature classes and related attribute tables required by the USGS. Initial mine waste inventory work focused on searching for and digitizing mine waste features throughout the western U.P. that exceeded the 2,000m<sup>2</sup> size requirement. The MGS team originally located and digitized 441 mine waste features by utilizing LiDAR-derived, 1-meter DEMs, 2024 ESRI areal imagery, and published geologic maps. This process is depicted by a simplified workflow shown in Figure 2. The mine waste features were then filtered based on their size. Those smaller than 2,000m<sup>2</sup> were omitted from the master dataset. Corresponding attribute tables were then populated with data from publicly available literature, websites, state and federal datasets, and information archived in the state's drill core repositories. The final databases will ultimately comprise the most up-to-date record of the volume, tonnage, grade, and mineralogy of Michigan's legacy mine waste sites.

Future MGS work within the scope of the Earth MRI Mine Waste Cooperative Agreement is a mine waste characterization effort, which aims to sample and evaluate nonfuel mine waste sites that potentially contain critical minerals. This project will begin in 2025 and continue through 2026.

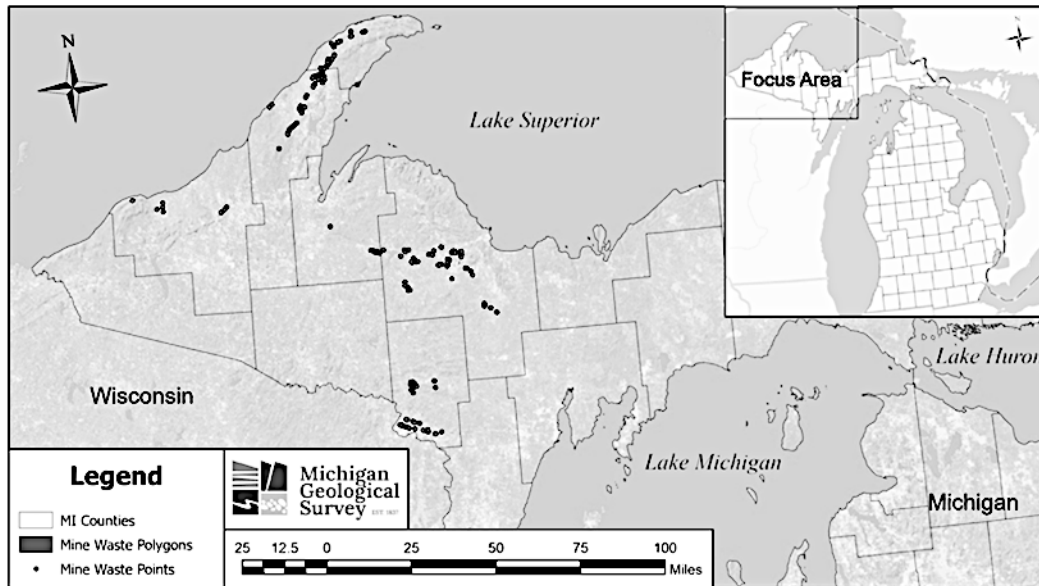


Figure 1. Map displaying all mine waste features inventoried and submitted to the USGS for the fiscal year 2023 Priority 1 funding represented as purple points and polygons.

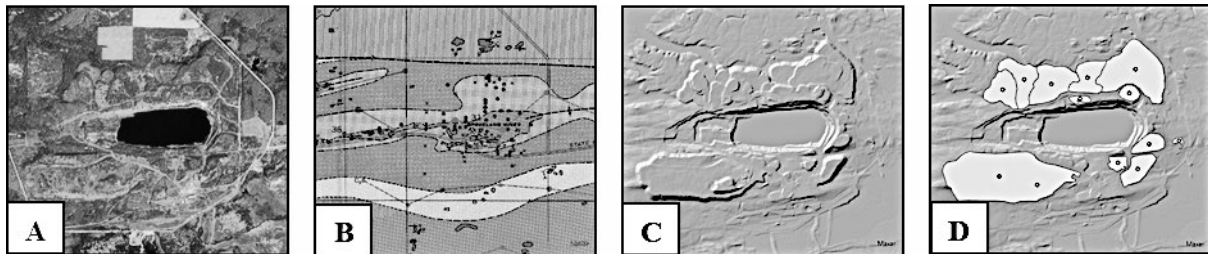


Figure 2. Simplified process to locate and digitize the mine waste features using ArcGIS Pro coupled with online sources. A.) ESRI imagery (Esri, 2024); B.) Bedrock geology of central Dickinson County, MI (James and others, 1961); C.) 1-m QL2 LiDAR DEM model; D.) Digitization of mine waste features.

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## **Critical Mineral Potential of the Northern Margin of the Watersmeet Gneiss Dome, MI USA**

**QUIGLEY, Ashley K.<sup>1</sup>, MAHIN, Robert A.<sup>1</sup>, and GAMET, Nolan G.<sup>1</sup>**

<sup>1</sup>*Michigan Geological Survey, Western Michigan University, 416 Avenue C Gwinn, MI 49841*

Precambrian gneisses and schists on the northern margin of the Watersmeet Dome in Michigan have been shown to be unusually enriched in rare earth elements, fluorite and incompatible elements including U, Th, Hf, and Zr (Barovich et al., 1991; Sims, 1990). The area is within two Earth Mapping Resources Initiative (EMRI) critical mineral focus areas for IOCG/IOA and magmatic REE deposits (Dicken and others, 2022). To further assess the potential for critical minerals, the Michigan Geological Survey (MGS) is conducting detailed geologic mapping and sampling, as well as collecting geophysical and geochronological data.

The project area is roughly 36 square kilometers on the border of Gogebic and Ontonagon Counties and 10 kilometers northwest of the town of Watersmeet, MI. Field work began in July of 2024 with a projected completion date in early 2026.

During the 2024 field season, the MGS mapped, described and recorded 620 outcrops in the project area using ArcGIS Field Maps and submitted 124 samples for whole rock and trace element geochemistry. An RS-230 BGO gamma-ray spectrometer was used to take over 600 total gamma (K/U/Th) measurements from outcrop. Additionally, a drone-borne, high resolution magnetic survey was flown over areas where permission was granted by landowners.

Preliminary field observations include the presence of fluorite in outcrop spatially associated with magnetic and gamma count anomalies. The results of the lithogeochemistry show a strong spatial correlation between fluorine, uranium, thorium, and total REEs. When rare earth element concentrations were converted to industry standard rare earth oxides (REOs), 14 samples had total rare earth oxide (TREO) values greater than 1,000 ppm (Hellman and Duncan, 2018). Geophysical, analytical, and field data also identified an anomalous magnetic high approximately 500m x 300m associated with previously undescribed REE-bearing, magnetic, fine-grained schists.

In 1982, Rocky Mountain Energy (RME) conducted exploration drilling for uranium based on anomalous gamma radiation in outcrop. A reexamination of the core found chalcopyrite in close association with fluorite. The presence of anomalous F, Cu, U, REE and magnetite is suggestive of an IOA/IOCG footprint (Hitzman, 2000). This will be investigated using IOCG discrimination diagrams such as Montreuil and others (2013).

Barovich et al. (1991) observed that the elevated REEs, fluorite and incompatible elements were tied to a gneiss and schist unit with an interpreted Paleoproterozoic age between 1.9 and 1.7 Ga, much younger than the Archean aged rock units that make up most of the Watersmeet gneiss dome. Because of the apparent link between rock age and critical minerals, confirming existing ages with modern U-Pb dating techniques, as well as adding ages from new locations, is an important piece of this study. Five samples were submitted for U-Pb geochronology of zircon grains. Results are pending.

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## **Plume control on the initiation of Mid-Continent Rift breakup using Unconformities: Implications for the Tectono-magmatic evolution and mineral deposits**

**ROHRMAN, Max<sup>1</sup>**

<sup>1</sup>*DECAN Geosolutions, PO Box 131148, Houston, TX 77219*

Regional unconformities from the stratigraphic record interpreted on existing Multi Channel Seismic (MCS) data obtained by Grant Norpac/Argonne (red numbered) and the GLIMPCE program (red lettered) (Figure 1A), are used for temporal and spatial control on Mid-Continent Rift (MCR) evolution. This allows identification of key events in the evolution of the rift, whereas potential field data, seismic refraction and Rayleigh waves, help constrain spatial and quantitative constraints. Based on magmatic stage definition, two regional unconformities were interpreted from MCS data: MU (Magmatic Unconformity), at the top of the Main stage (~ 1100 – 1089 Ma), signaling the end of major flood basalt magmatism, and BU (Breakup Unconformity) representing the Latent stage (~ 1104 – 1100 Ma). The latter is observed as a sequence at Mamainse Point (Figure 1), rather than an unconformity, stressing the importance of spatial control on events. Magmatic crustal thicknesses and lower crustal seismic velocities obtained from MCS and refraction data (Shay and Trehu, 1993) are used to constrain relative importance of important parameters in melt production, such as: potential temperature, active mantle upwelling and lithospheric thinning. Together, these data suggest that the MCR originated from an earlier NW-SE pre- or proto-rift (blue, Figure 2A) recognized from outcrop (Figure 1A) and MCS, further reconstructed by aligning Archean granitic blocks such as White Ridge (WR), Grand Marais (GM) and Wawa-Abitibi (purple, WA) from gravity lows (Figure 1B, 2A). The area was affected by a plume constrained by a Rayleigh Wave Low Velocity Anomaly (RWLVA) (Foster et al., 2020) (Figure 1A). This generated uplift in central Lake Superior focused on a region around the Coldwell Complex (Figure 1A). Subsequently, Early-stage (~ 1110 - 1104 Ma) magmatism in the proto-rift generated by NE-SW extension along strike slip faults such as the Thiel Fault (TF) (Figure 1A), in the central and eastern arm of the MCR.

By the end of the Early-stage, the plume was deeply embedded in the lithosphere and initiated the start of a thick N-S crustal ridge or proto-hotspot track in central Lake Superior during the late Early- to Latent stage (Figure 2B,C). After a break in activity recorded by the Breakup Unconformity (BU), the plume moved relatively southward during the Main-stage and possibly influenced stress re-orientation to N-S (Figure 2D). This locked the eastern arm and locally, new thick oceanic crust formed along the syncline in central Lake Superior, generating the western rift arm. However, magmatism and breakup terminated shortly after as a result of Grenvillian compression, evidenced by the Magmatic Unconformity (MU).

During the Main stage, active upwelling and anomalously thick oceanic crust formation was highest on the crustal ridge (black dash-dot line, Figure 2D), measured at line A, just north of the WA block (purple arrow, Figure 2D) and decreasing toward line C (purple arrow). Further west, at St Croix, upwelling rates approach unity and no oceanic crust formation took place. Pulsing and waning of the plume stem/conduit through time (Figure 2) is recorded in the unconformities, suggesting a drop in potential temperature and upwelling rate around BU time (Latent stage) (Figure 2C).

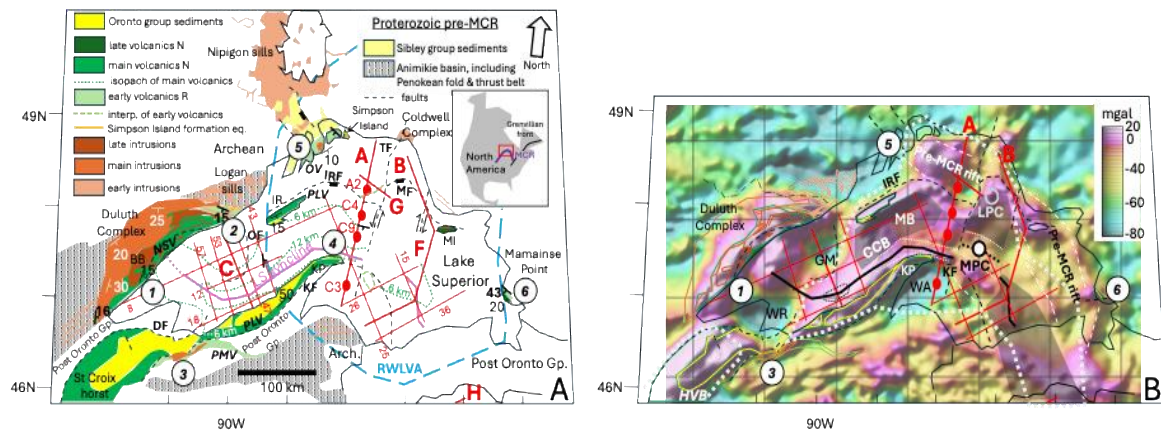


Figure 1: A. Geological map with seismic lines (red). Numbering refers to onshore geological sections. B. Gravity map. Abbreviations: MB Marquette Basin, KP Keweenaw Peninsula, HVB High Velocity Body.

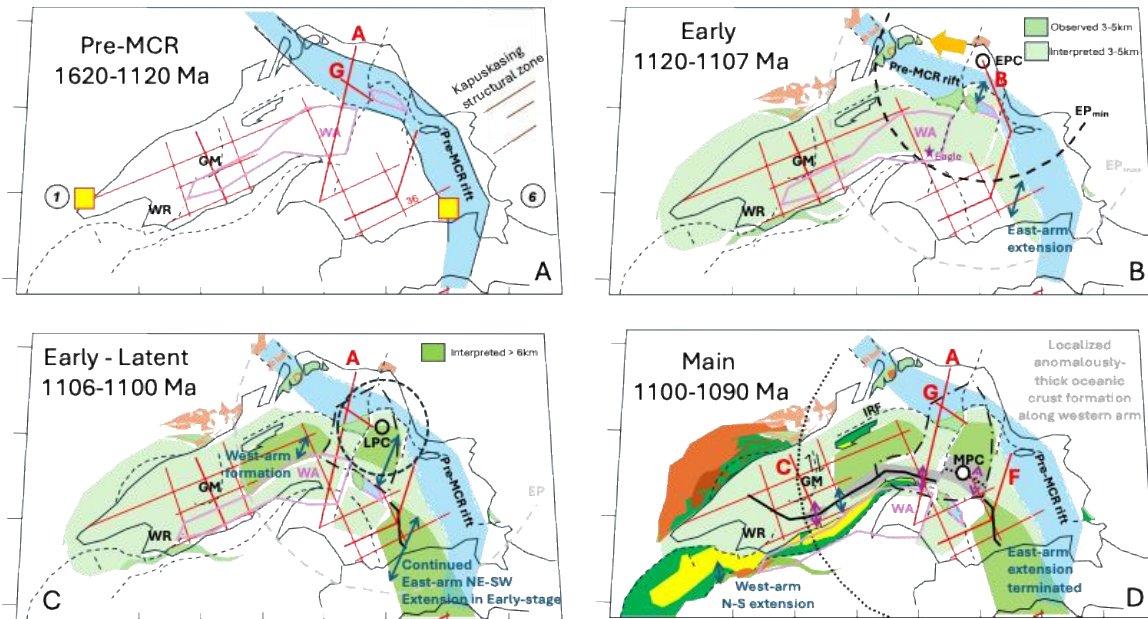


Figure 2: Tectono-magmatic evolution. South shore (between yellow cubes) is mobile, North shore is kept fixed. EPC Early Plume center, LPC Latent Plume Center, MPC Main Plume Center.

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## Constraining the timing of crustal exhumation following the Penokean orogeny using U-Pb, Sm-Nd, and Lu-Hf geochronology and microstructural analysis

SALERNO, R.,<sup>1</sup> CANNON, W.F.,<sup>1</sup> SOUDERS, A.,<sup>2</sup> THOMPSON, J. M.,<sup>2</sup> VERVOORT, J.,<sup>3</sup>

<sup>1</sup>*U.S. Geological Survey, Reston, VA 20192*, <sup>2</sup>*U.S. Geological Survey, Denver, CO 80225*, <sup>3</sup>*Washington State University, Pullman, WA 99164*.

Precambrian terranes in the Lake Superior region have complex igneous, metamorphic, and deformational histories spanning the Eoarchean to the Neoproterozoic. In this sequence, the Penokean orogeny (1880–1830 Ma) is the first collisional event in a long-lived subduction system on Laurentia's southern margin, marking a transition in the style of Laurentian assembly from the amalgamation of disparate Archean cratons to growth by accretion of juvenile arcs. The metamorphic and structural history of the corridor of Archean gneiss domes south of Lake Superior is typically attributed to the Penokean orogeny. However, recent <sup>40</sup>Ar/<sup>39</sup>Ar geochronology calls this relationship into question as ~1760 Ma cooling ages across the region indicate the deformation and metamorphism coincident with dome uplift is markedly younger (Schneider et al., 2004; Tinkham and Marshak, 2004; Holm et al., 2005; Schulz and Cannon, 2007). To correctly distinguish the effects of the Penokean orogeny and more accurately reconstruct the Paleoproterozoic tectonic history of the Upper Midwest, we present new U-Pb, Sm-Nd, and Lu-Hf geochronology and microstructural analyses for a suite of metamorphosed and deformed rocks within and adjacent to several gneiss domes (Fig. 1).

Titanite U-Pb ages and trace element compositions reflect Archean metamorphism at  $2550 \pm 46$  Ma (2SE), and variable degrees of recrystallization in the Paleoproterozoic (Fig. 2). Apatite and monazite U-Pb ages, along with garnet Lu-Hf ages of metamorphosed supracrustal rocks directly outside of domes, record the onset of peak conditions by  $1837 \pm 7$  Ma that continued beyond the end of the Penokean orogeny until  $1782 \pm 15$  Ma. The garnet Sm-Nd ages of several samples are ~70 Ma younger than the Lu-Hf ages, reflecting a period of cooling and exhumation between  $1752 \pm 10$  and  $1738 \pm 9$  Ma. This exhumation interval overlaps with the U-Pb ages of syn-kinematic titanite at  $1713 \pm 32$  Ma and the  $1750 \pm 6$  Ma Lu-Hf age of re-equilibrated pre-kinematic garnets. U-Pb ages of apatite in one sample reflect much later reheating of the system at  $1592 \pm 26$  Ma. These data show that deformation and metamorphism related to the uplift of gneiss domes in the Lake Superior region can only be partially linked to tectonic events between 1880–1830 Ma. Peak metamorphic conditions lasting until 1782 Ma indicate the persistence of thick orogenic crust well after the end of the Penokean orogeny—perhaps supported by continued convergence or an unrecognized collisional event along the margin. Exhumation beginning at 1752 Ma coincided with subduction farther south during the Yavapai orogeny (1760–1720 Ma), whereas uplift may be related to crustal extension above the downgoing slab, aided in part by gravitational forces acting on overthickened crust. Extension during this time would also have played a role in the generation and spatial accommodation of Yavapai-age granite intrusions across the region (e.g., East-Central Minnesota batholith). The youngest apatite U-Pb age at 1592 Ma likely represents distal thermal effects of the Mazatzal orogeny (1650–1600 Ma) farther south. These data reveal the gneiss dome structures in the Upper Midwest are the result of a protracted history including several Paleoproterozoic metamorphic, deformational, and uplift events spanning more than 70 m.y..

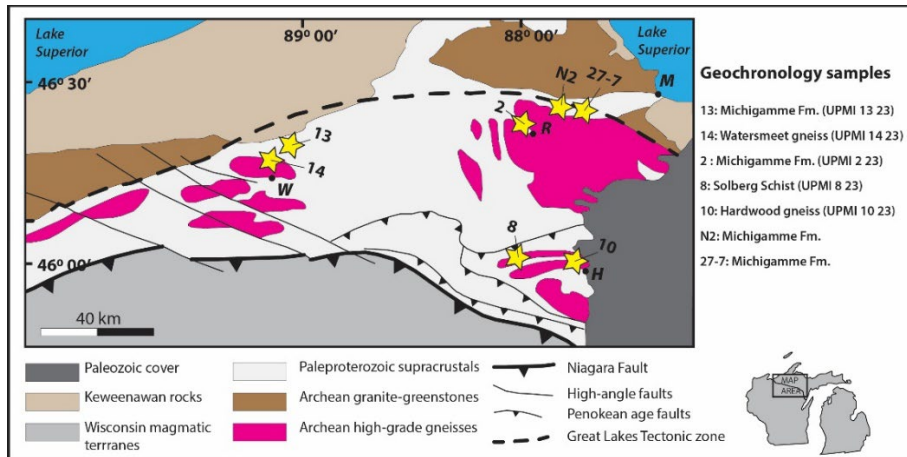
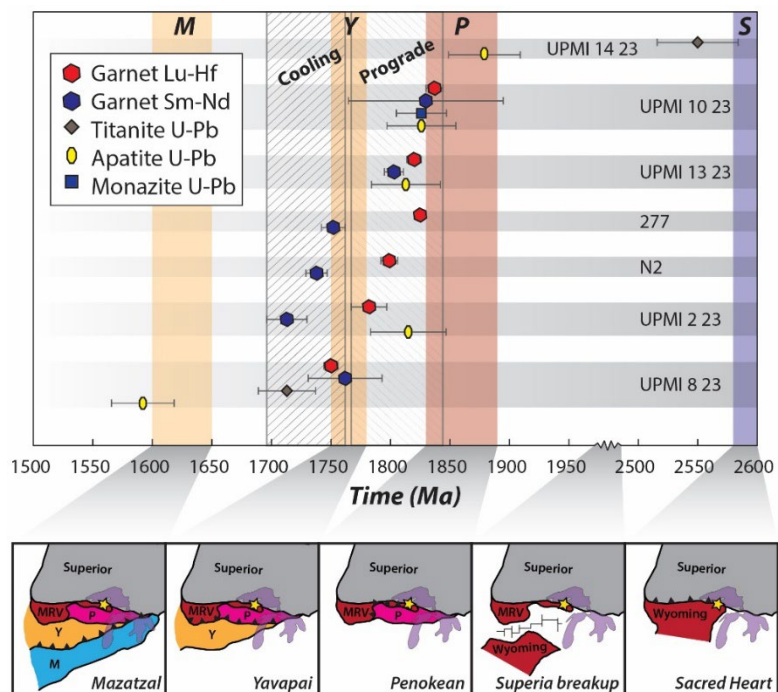


**Figure 1:** Left, geologic map showing gneiss domes in northern Michigan with geochronology sample sites. Cities shown – Marquette (M), Watersmeet (W), Republic (R), and Hardwood (H). Modified from Tinkham and Marshak (2004).

**Figure 2:** Right, ages at 2SE precision. Vertical bars represent the timing of the Sacred Heart (S), Penokean (P), Yavapai (Y), and Mazatzal (M) orogenies. Hatched fields represent durations of metamorphic prograde and cooling intervals. Sm-Nd ages of UPMI 10 23 and UPMI 8 23 have high uncertainties from mineral inclusions that could not be removed prior to analyses and therefore are not used to define the duration of the cooling interval. Diagrams below show the Archean-Mesoproterozoic tectonic evolution of southern Laurentia. Yellow star shows study area location.



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## Identifying Abandoned Mine Surficial Features Using Mask R-CNN, Upper Peninsula Michigan.

SHALIFOE, MaryElizabeth<sup>1</sup>, VOICE, Peter<sup>1</sup>

<sup>1</sup>*Department of Geological and Environmental Sciences and Michigan Geological Survey, Western Michigan University, 1903 W Michigan Ave, Kalamazoo MI, 49008-5241, USA*

From the 1840s to the 1980s, iron, and copper mining in Michigan's Upper Peninsula thrived, leaving behind numerous surficial features from the early underground mining practices. Even today the Eagle Mine located in Marquette County is still active Mining both copper and nickel. Today's demand for rare earth minerals has sparked interest in exploring locations near these primary ores including the tailing piles (Demas A., 2023). Mapping old mine features using optical satellite imagery is challenging in Michigan's Upper Peninsula due to dense vegetation and snow cover – instead we need to use techniques that allow us to see through this cover.

This study aims to assess the performance of object detection Deep Learning Models (DLMs) in mapping potential mine features using high-resolution terrain data (LIDAR-derived 1-meter Digital Elevation Models) produced through the 3D Elevation Program. Dickinson County was chosen as the study area due to its rich history of 52 known abandoned mines within the East Menominee Iron Range (Figure 1). This study targeted various features, such as prospect pits, open pits, lateral ditches, and waste piles, resulting in a total of 946 identified features used for training the DLMs.

The object detection methods available within ArcGIS software were evaluated including Feature Classifier, Faster R-CNN, and Mask R-CNN. Our initial evaluation has shown that Mask R-CNN performed better than the other methods, due to the Mask R-CNN method that enables pixel-level segmentation in addition to object detection (Maxwell A. E., et al., 2020). Our ongoing work is focused on the refinement of the model parameters to better locate surface features related to historic mining. Once the model is completed, it will be tested on various locations in northern Michigan within the mining ranges of the Marquette Iron Range, Menominee Iron Range, Gogebic Iron Range, and the Copper Ranges within Ontonagon and through the Keweenaw. This will then be ground-truthed, by going out into the field to verify the locations of the features or using historical topographic maps to verify the existence of features that may be inaccessible.

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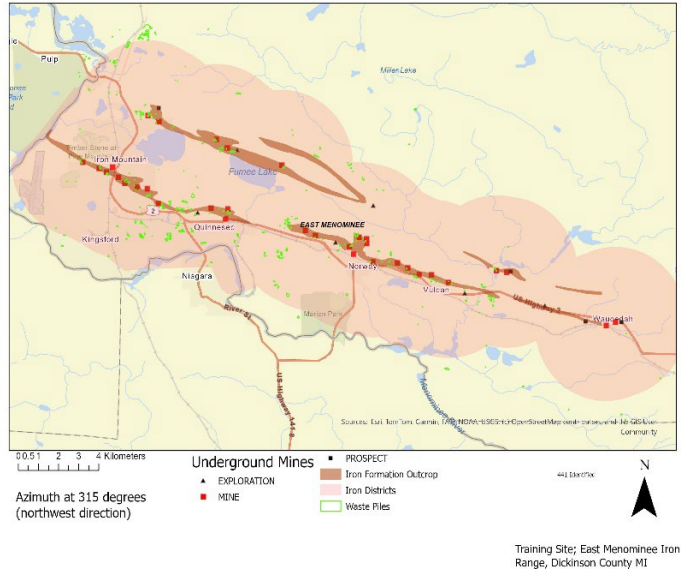


Figure 1: Study Area in Dickinson County, showing the distribution of underground mines (Department of Environment, Great Lakes, and Energy, 2024).

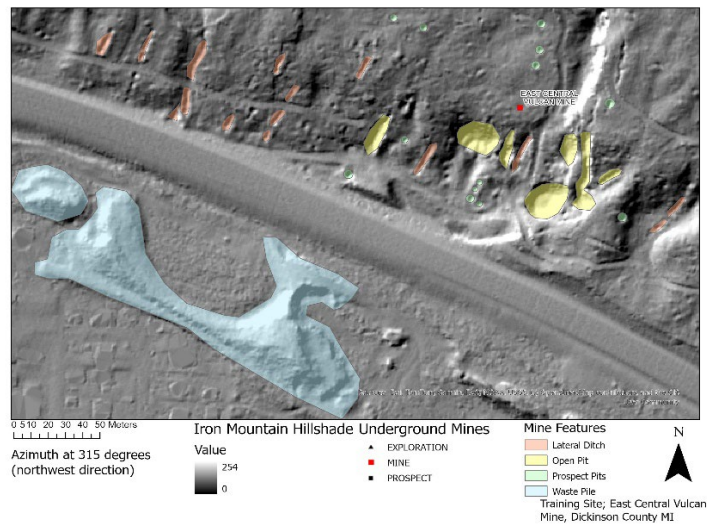


Figure 2: Mine Features located near East Central Vulcan Mine in Dickinson County, DEM sourced USGS TNM, 2016. (Department of Environment, Great Lakes, and Energy, 2024).

## Basaltic rocks of the Animikie Group in Ontario: Geochemical characteristics and tectonic significance

SMYK, Mark<sup>1,3</sup>, HOLLINGS, Pete<sup>1</sup>, METSARANTA, Riku<sup>2</sup>, CUNDARI, Robert<sup>3</sup>, KISSIN, Stephen<sup>1</sup> and KURCINKA, Colleen<sup>3</sup>

<sup>1</sup>*Department of Geology, Lakehead University, 955 Oliver Road, Thunder Bay, ON P7B 5E1 Canada*

<sup>2</sup>*Ontario Geological Survey, Ministry of Mines, 933 Ramsey Lake Road, Sudbury, ON P3E 6B5 Canada*

<sup>3</sup>*Ontario Geological Survey, Ministry of Mines, 435 James St. South, Thunder Bay, ON P7E 6S7 Canada*

The Paleoproterozoic Animikie Group in Ontario records a history of continental sedimentation and minor volcanism on the southern margin of the Superior Craton between ca. 1.88 Ga and 1.82 Ga. Both the chemical sedimentary rock-dominated Gunflint Formation and overlying, siliciclastic sedimentary rock-dominated Rove Formation contain significant intervals of tuffs and basalt flows. Copper-bearing amygdaloidal basalts were noted in Crooks and Blake townships (Coleman 1900); basalt flows and tuffs were identified by Gill (1925) and Goodwin (1960) in the Mink Mountain area, and by Tanton (1931) in Oliver Township. Tanton (1936) mapped “Rove basalt” in Devon Township. In 2022, a 774 m diamond drill hole (DDH ST-22-01), completed by Metal Energy Corp. in Hartington Township, provided a complete section from Rove Formation into Archean basement. New geochemical, petrographic and stratigraphic data gleaned from this drill core and recent field work have provided insights into the nature of the basaltic rocks.

The lowermost volcanic unit occurs in the middle of the Gunflint Formation, exposed near Mink Mountain; its base is ~53 m above Archean basement. Approximately 21 m thick, it consists of several distinctive, typically massive, locally pillowed, vesicular/spherulitic basalt flows. An isolated outcrop of amygdaloidal basalt in Oliver Township, approximately 40 km northeast of Mink Mountain, shares similar petrographic characteristics, stratigraphic position and geochemistry. Limited geochemical data gleaned from amygdaloidal basalts in Crooks Township are similar to those of the aforementioned Gunflint lavas. Further work is required to elucidate the nature and stratigraphic position of these flows.

Basaltic flows, exposed on top of Rove shales and wackes in Devon Township (Cundari, 2010) had recently been considered part of the Mesoproterozoic Midcontinent Rift, based mainly on a Keweenawan reversed paleomagnetic mean direction and equivocal stratigraphic constraints (Cundari et al., 2012). However, a mafic interval, approximately 510 m above Archean basement and ~4 m thick, occurs within DDH ST-22-01 and displays a variolitic, chilled basal contact and spherulitic, vesicle-like features, similar to those displayed by the lowermost Devon flows.

Similar trace element geochemistry further supports the contention that the mafic rocks intersected in drilling may be correlative with the Devon basalts and with other, similar rocks exposed in an isolated outcrop in Hardwick Township, ~30 km northwest of the Devon basalts. The Gunflint basalts are characterized by moderate La/Sm<sub>CN</sub> ratios (~1.9 to 3.9), negative Nb-Ta and Ti anomalies and relatively flat Gd/Yb<sub>CN</sub> ratios (~1.3 to 1.7). The Devon basalts are characterized by moderate La/Sm<sub>CN</sub> ratios (~2.8 to 3.5), negative Nb and Ti anomalies and moderate Gd/Yb<sub>CN</sub> ratios (~3.0-3.6).

In a Penokean tectonic context, the Gunflint basalts may represent limited back-arc volcanism (cf. Kissin and Fralick, 1994), contemporaneous with the older phase of volcanism in the Pembine domain of the Pembine-Wausau terrane (PWT; ca. 1875 Ma, Zi et al. 2022). The Devon basalts may represent relatively deeply sourced, crustally contaminated, OIB-like magmas generated after ca. 1840 Ma, at the same time as renewed volcanism in the PWT.

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## Sedimentologic and geochemical evidence of marine incursion to the Oronto Group basin, southern Lake Superior region, at ca. 1.08 Ga

STEWART, Esther K.<sup>1,2</sup>, TAPPA, Michael<sup>1</sup>, BAUER, Ann<sup>1</sup>, BRENGMAN, Latisha<sup>3</sup>, and PRAVE, Anthony<sup>4</sup>

<sup>1</sup>Department of Geoscience, University of Wisconsin-Madison, Madison, Wisconsin 53705

<sup>2</sup>Wisconsin Geological and Natural History Survey, University of Wisconsin-Madison Division of Extension, Madison, Wisconsin 53705

<sup>3</sup>Department of Earth and Environmental Sciences, University of Minnesota-Duluth, Duluth, Minnesota 55812

<sup>4</sup>School of Earth and Environmental Sciences, University of St. Andrews KY16 9TS, Scotland/UK

The late Mesoproterozoic Oronto Group (Copper Harbor Conglomerate, Nonesuch, and Freda Formations), Wisconsin and Michigan, preserves a continuous record of depositional environment and related microbial habitat. Over three kilometers of siliciclastic sediments with minor authigenic, molar tooth calcite record physical and biogeochemical processes acting within the Oronto Group basin at the time of deposition and early diagenesis. Combined sedimentologic and geochemical evidence motivates reevaluation and refinement of evolving depositional conditions (Stewart, 2025). Sedimentary facies indicate a shallow marine, tidal influence on deposition, requiring marine incursion to the Laurentian interior at ca. 1.08 Ga (Stewart et al., 2024). The degree of marine connectivity is investigated using C, O, and Rb-Sr isotope compositions of calcite microspar in molar tooth structures and carbonate laminae of the Nonesuch Formation. Molar tooth structures and laminae were milled from thick sections, and one split of sample powder was analyzed for C and O isotopes while the other underwent a multistep chemical separation process to isolate Rb-Sr isotopes from calcite. Carbon isotope ( $\delta^{13}\text{C}$ ) values (-3.9 to -2.0‰) of earliest diagenetic calcite reflect organic matter remineralization driven by *in situ* microbial carbon cycling (e.g. Gilleaudeau and Kah, 2013). Values of  $\delta^{18}\text{O}$  (-6.7 to -3.6‰) measured in the calcite microspar of molar tooth structures overlap the isotopic signature of marine carbonates from other late Mesoproterozoic evaporative marine basins (e.g. Kah, 2000). The  $^{87}\text{Sr}/^{86}\text{Sr}$  of least-altered calcite (~0.7068 to 0.7069) reflects marine mixing with continental runoff. Combined, these data reflect deposition within a restricted-marine epeiric setting. In addition to isotopic evidence for marine connectivity, conditions of salinity, redox, and productivity are evaluated using whole rock geochemistry of fine-grained siliciclastics and rare earth element + yttrium (REY) distributions of calcite microspar. Whole rock geochemistry was compiled from published sources and new data was collected from two cores in Wisconsin. Calcite REY distributions were analyzed from aliquots of the same sample material processed for Rb-Sr isotopes. Shale geochemistry, including Mo and U enrichment and stratigraphic trends in proxies for detrital input (Zr, Al), redox (S, TOC) and productivity (Ba, P) reveal deposition within an oxidized basin with a deep, fluctuating chemocline and expansion of anoxic and euxinic conditions during maximum flooding and base level lowstand. REY distributions of calcite microspar preserve an early diagenetic estuarine signal characterized by muted, positive La and Y/Ho anomalies and heavy REE enrichment. Shale geochemistry and carbonate REY distributions bring into focus the prevalence of particle shuttling between the water column and shallow sediments that likely enhanced and focused nutrient P bioavailability, analogous to modern estuarine nutrient cycling. Collectively, these data provide a richer understanding of late Mesoproterozoic environmental conditions that influenced early eukaryote ecology.

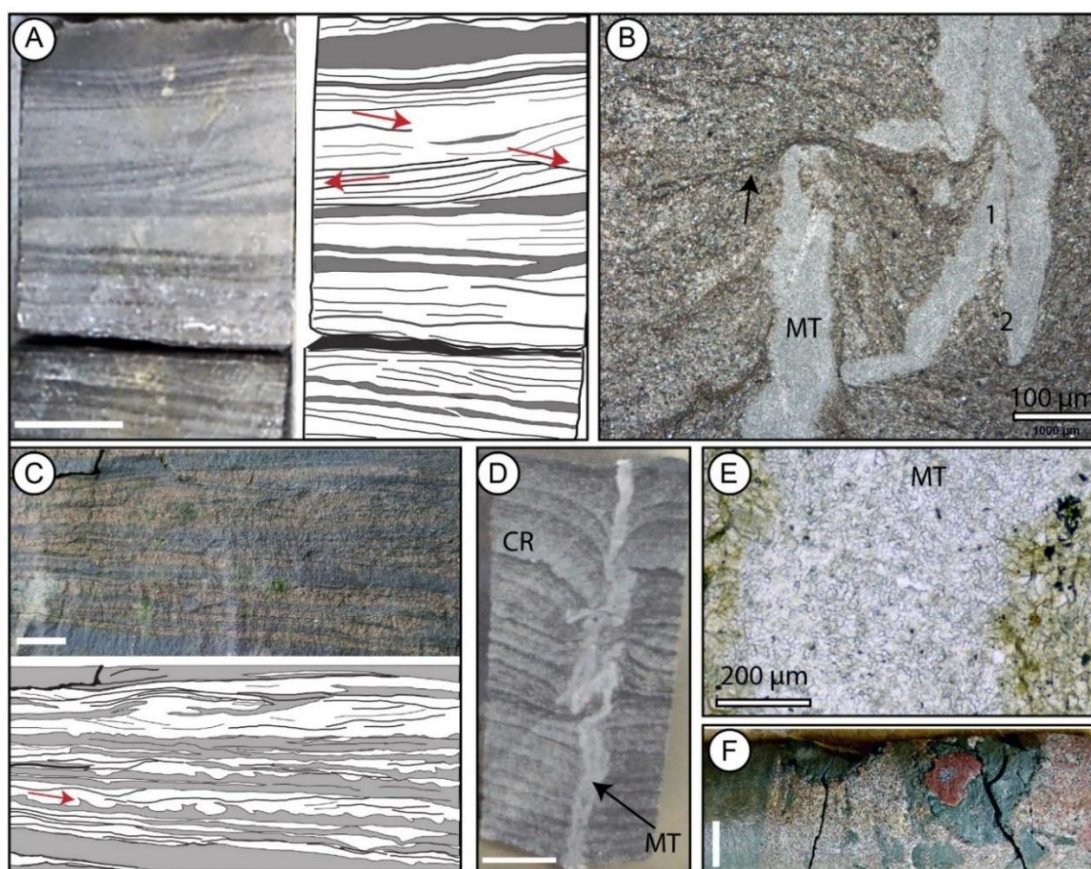


Figure 1: Images from core (A, C-D, F) and thin section (B, E) of the Nonesuch Formation highlighting sedimentary structures indicative of tidal influence and molar tooth calcite microspar targeted for geochemistry. A & C: photos and line drawings showing close association of fine-grained sandstone (light color) and shale (dark color). Note mud drapes on bi-directional ripple laminae (red arrows, A), flame structures (red arrow, C), and structureless mud layers indicative of fluid mud deposits. B: Photomicrograph (cross-polarized light) showing bedding deflecting around molar tooth structure (arrow) and brittle deformation of molar tooth structures (1 displaced from 2). D: molar tooth structure (MT) cross-cutting carbonate-rich layers (CR) in drill core. E: Photomicrograph (plane-polarized light) highlighting characteristic molar tooth microspar texture. F: Core photo showing ~2 cm diameter mud ball with subangular rhyolite clast at its core. Scale bars are 1 cm unless otherwise noted.

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**Midcontinent Rift extension ceased and the rift inverted due to the Grenvillian orogeny**  
**SWANSON-HYSELL, Nicholas<sup>1</sup>, HODGIN, Eben B.<sup>2</sup>, ALEMU, Tadesse<sup>3</sup>, FUENTES, Anthony<sup>4</sup>, ZHANG, Yiming<sup>2</sup>, SLOTZNICK, Sarah<sup>5</sup> and FAIRCHILD, Luke<sup>4</sup>**

<sup>1</sup>Department of Earth and Environmental Sciences, University of Minnesota, Minneapolis, MN, USA

<sup>2</sup>Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI, USA

<sup>3</sup>Department of Geology and Environmental Science, University of Wisconsin, Eau Claire, WI, USA

<sup>4</sup>Department of Earth and Planetary Science, University of California, Berkeley, CA, USA

<sup>5</sup>Department of Earth Sciences, Dartmouth College, Hanover, NH, USA

The cessation of rifting within the Midcontinent Rift was a key event in the evolution of the Lake Superior region. If rifting had continued and led to the formation of an ocean basin, the subsequent geologic and paleogeographic history would have been profoundly different. In a 1994 paper, Bill Cannon used emerging geochronology from the Midcontinent Rift and the Grenville orogen to conclude that the closing of the Midcontinent Rift was a far-field effect of compression associated with the Grenvillian orogeny (Cannon, 1994). An alternative proposal was put forward by Stein et al. (2014) who proposed that the Midcontinent Rift is an abandoned rift segment associated with successful rifting along Laurentia's margin. In this contribution, we leverage improved chronostratigraphy within the volcanics and sedimentary rocks of the Midcontinent Rift (e.g. Fairchild et al., 2017; Hodgin et al., 2024) combined with rich new records of metamorphic chronology associated with the Grenvillian orogeny (reviewed in Swanson-Hysell et al., 2023) to revisit this question and gain fresh insight.

The transition from active rift extension to post-rift thermal subsidence is recorded by the Brownstone Falls angular unconformity in northern Wisconsin. The thinning of the Copper Harbor Conglomerate from >2,200 m thick on the Keweenaw Peninsula of Michigan to pinching out against the unconformity implies topographic relief at the onset of post-rift sedimentation that is comparable to that in the modern-day East African rift. The end of active extension (ca. 1090 to 1085 Ma) is coincident with early prograde metamorphism associated with the Grenvillian orogeny, whose metamorphic imprint extends from the Blue Ridge inliers of the eastern US up through the Grenville Province of eastern Canada. This timing is consistent with the onset of continent-continent collision resulting in the cessation of extension in the rift.

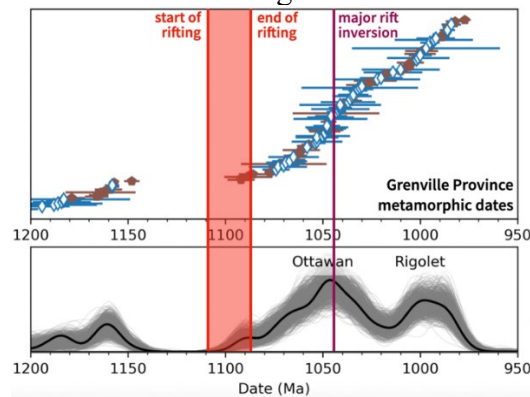


Figure 1: The start and end of Midcontinent Rift extension compared with U-Pb dates from Grenville Province metamorphic chronometers (blue diamonds: zircon; red pentagons: monazite). The rift developed during an interval of tectonic quiescence on the margin. Extension ceased with the onset of the Grenvillian orogeny and the rift contractionally inverted during the peak of the Ottawan stage.

Following the end of Midcontinent Rift extension, deposition of the Oronto Group continued until ca. 1045 Ma (Hodgin et al., 2024; Fuentes et al., in review). This deposition resulted from post-rift thermal subsidence prior to contractional deformation associated with the Grenvillian orogeny propagating into the continental interior. Paleomagnetic records from the Oronto Group, including recently published data from the Nonesuch Formation (Slotznick et al., 2024) and new unpublished data from the upper Freda Formation, reveal that Laurentia's plate motion dramatically slowed coincident with the onset of Grenvillian orogenesis. Preceding rapid motion was associated with ocean basin closure leading up to continent-continent collision that changed the force balance and slowed the plate.

Oronto Group deposition ended when contractional deformation associated with the Grenvillian orogeny propagated into the Midcontinent. This deformation occurred in two phases with major exhumation occurring during the peak of the Ottawan phase of the Grenvillian orogeny and a second more minor phase of ca. 1000 to 980 Ma contraction associated with the Rigolet phase (Hodgin et al., 2024). This final interval of contraction is associated with the ca. 990 Ma deposition of the Jacobsville-Bayfield Group (Hodgin et al., 2022; Alemu et al., 2023). Following 130 Myr of tectonic excitement from ca. 1110 to 980 Ma, stability returned to Laurentia's Midcontinent region. While the comings and goings of inland seas and the occasional impact crater have left their mark on the geological record, there has been only very minor tectonism over the past billion years.

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## Ni-Cu-PGE Mineralization at the Mineral Lake Intrusive Complex, northern Wisconsin

THOMPSON, Bekah R. <sup>1</sup>, LODGE, Robert W.D.<sup>1</sup>

<sup>1</sup>Department of Geology & Environmental Science, University of Wisconsin-Eau Claire, 105 Garfield Avenue, Eau Claire, WI 54701, USA

The Mineral Lake Intrusive Complex (MLIC), near Mellen, Wisconsin, is a 1.1 Ga layered and differentiated mafic intrusive complex within the Mesoproterozoic Mid-Continent Rift in the Lake Superior region (Siefert et al., 1992). This intrusive complex hosts Ni-Cu-PGE mineralization discovered in the 1960's via electromagnetic geophysical surveys and at least 16 drill holes were completed (Bakheit, 1981). With an increase in demand for domestic critical minerals to supply metals for energy, communication, and military infrastructure, underexplored prospects like the Mineral Lake Ni-Cu-PGE prospect are increasingly important. This project aims to describe the mineralogy of the sulfide inclusions and the host intrusion geochemistry to better understand the geological characteristics of PGE-mineralization within the MLIC.

Two drill holes were re-logged (WIS-12 and WIS-11), totaling ~950 linear feet of core, and sixteen samples were collected from representative intrusive phases and mineralization types. Micron-scale PGE-bearing mineral phases are described using the SEM-EDS. Whole rock geochemistry of the MLIC was completed via X-ray Fluorescence (WD-XRF). Silicate and sulfide mineralogy was determined by transmitted and reflected light petrography.

Mineralization is hosted in either medium-grained, equigranular olivine gabbro, olivine norite and troctolite phases of the intrusion and are found as mm-scale sulfide segregations composing 1-10% of the rock. Weak foliation and alteration along fractures are observed along brittle-ductile shears resulting in serpentinization of olivine. Contacts between intrusive phases are generally gradational over a few centimeters. Sulfide inclusions contain varying amounts of chalcopyrite, pyrrhotite, and pentlandite and are not obviously correlated with any specific intrusive phase. Graphite, both fracture-associated and matrix-associated, were observed in the Troctolite and Olivine norite phases.

Sulfide inclusions are comprised of primarily pyrrhotite with variable amounts of chalcopyrite and pentlandite. Analysis on the SEM-EDS has shown PGE mineralization is commonly hosted as micron-scale inclusions within pyrrhotite and pentlandite. These PGE-bearing mineral phases include rhenium-bearing molybdenite (Mo,Re)S<sub>2</sub>, padmaite (PdBiSe) (found within silicates), argentopentlandite Ag(Fe,Ni)<sub>8</sub>S<sub>8</sub>, sperrylite (PtAs<sub>2</sub>), rhenite (ReS<sub>2</sub>), naldrettite (Pd<sub>2</sub>Sb). PGE minerals are typically ~5 microns. Notably large, 30-micron sperrylite (PtAs<sub>2</sub>) grains and 25-micron rhenite (ReS<sub>2</sub>) grains were observed (Figures 1C and 1D). PGE's are most abundant hosted in sulfide minerals whereas the notable critical elements (Bi, Mo, Sb, Te, Ob, Se) tend to be hosted in the silicates.

These results are comparable to other conduit-type and contact-type MCR intrusions, although the age of the MLIC is coeval with contact-type mineralization. Dunka road of the Duluth complex is a contact type Ni-Cu-PGE sulfide deposit. Phases include norite-hosted disseminated sulfides, troctolite-hosted disseminated sulfides, PGE-rich disseminated sulfides, and chalcopyrite rich disseminated sulfides (Theriault and Barnes, 1998). Since the MLIC is a large, differentiated intrusion that is coeval with other contact-type mineralization in the MCR, future exploration efforts and research should focus on the lower parts of the intrusion where dense sulfides may accumulate.

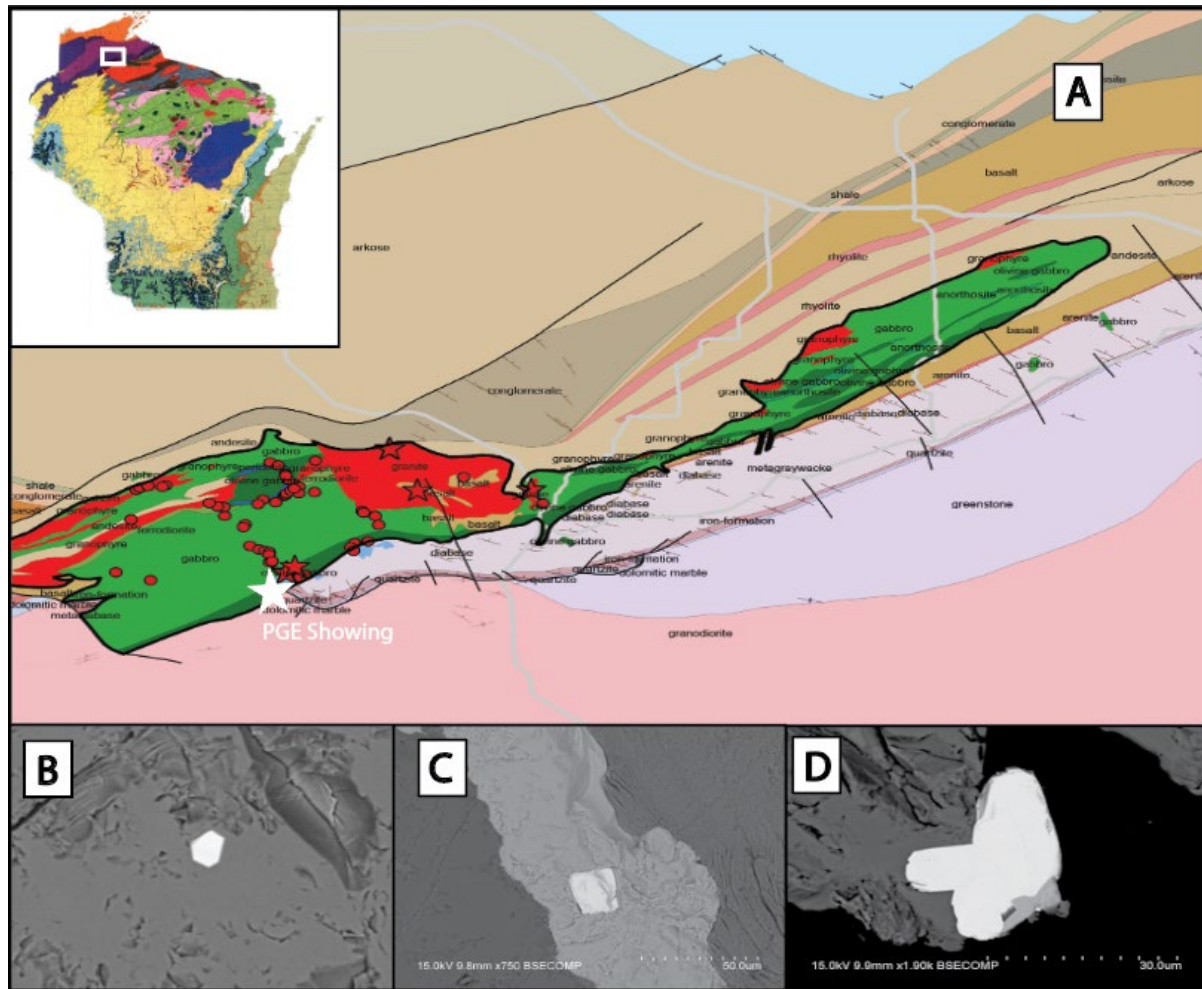


**Figure 1.** (A) Regional map of Mineral Lake area. Map modified from Cannon and Ottke (1999). Inset map from Mudrey & Brown (1982). (B) Rhenium-bearing molybdenite ( $(\text{Mo},\text{Re})\text{S}_2$ ) (white) under SEM-EDS, (C) Rhenite ( $\text{ReS}_2$ ) (white) under SEM-EDS, (D) Sperrylite ( $\text{PtAs}_2$ ) under SEM-EDS (white).

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**A Porphyry in a Rift? Constraining the Petrogenesis of the Jogran Porphyry, Mamainse Point, Ontario, Canada: Insights from Zircon and Melt Inclusion Geochemistry.**  
**TOLLEY, James<sup>1</sup>, HANLEY, Jacob<sup>2</sup>, CROWLEY, James<sup>3</sup>, TSAY Sasha<sup>4</sup>, ZAJACZ Zoltan<sup>4</sup>, and HOLLINGS, Pete<sup>1</sup>**

<sup>1</sup>Department of Geology, Lakehead University, 955 Oliver Road, Thunder Bay, ON, P7B 5E1, Canada.

<sup>2</sup>Department of Geology, Saint Mary's University, 923 Robie Street, Halifax, Nova Scotia, B3L 2Y5, Canada.

<sup>3</sup>Isotope Geology Lab, Department of Geosciences, Boise State University, 1910 University Drive, Boise, Idaho, 83725-1535, USA.

<sup>4</sup>Department of Earth Sciences, University of Geneva, Rue des Maraichers 13, Geneva, 1205, Switzerland.

The Jogran quartz-monzonite porphyry, located near Mamainse Point, Ontario, Canada, on the northeastern shoulder of the ~1.1 Ga Midcontinent Rift System (MRS), hosts unique porphyry-style Cu-(Mo) mineralization in an intra-plate, rift-related large igneous province setting (Perelló *et al.*, 2020). Combining high precision zircon geochronology with zircon and melt inclusion (MI) geochemistry refines the timing of emplacement and offers constraints on the crystallization temperature, oxygen fugacity ( $fO_2$ ), and melt composition (including ore metal tenor) during the magmatic evolution of the deposit.

A new high precision  $^{206}\text{Pb}/^{238}\text{U}$  zircon age of  $1090.90 \pm 1.27$  Ma (CA-TIMS) constrains the formation of the Jogran porphyry to the waning of the main Rift Stage (1102-1090 Ma) and synchronous with the transition to the Late-Rift stage (1090-1083 Ma), as defined by Woodruff *et al.*, (2020). Zircon geothermometry (Crisp *et al.*, 2023) and oxybarometry (Loucks *et al.*, 2020) suggest crystallisation conditions of 900-670 °C and a  $fO_2$  range of  $\Delta\text{FMQ} = -1.3$  to  $+0.6$ . As temperatures decrease,  $\Delta\text{FMQ}$  values increase along a trend subparallel to the  $\text{SO}_2\text{-H}_2\text{S}$  buffer. The presence of sulfide inclusions in zircon, confirms sulfide saturation during crystallization.

The analysed zircon crystals are zoned. They display an increase in  $[\text{Yb}/\text{Gd}]_n$  ratios (12-20) and concomitant depletion in  $\text{Th}/\text{U}$  (1.0-0.4) in the rims relative to the cores ( $[\text{Yb}/\text{Gd}]_n = <12$ ;  $[\text{Th}/\text{U}] = >1$ ). This zonation infers that the parental magma underwent a single stage of fractionation and crystallisation upon emplacement. Melt inclusions (MIs) range in composition from 65-70 wt.%  $\text{SiO}_2$  with 5.5-8.3 wt.%  $\text{K}_2\text{O}$  and  $\text{K}_2\text{O}/\text{Na}_2\text{O}$  ratios of ~1.5-3.5, suggesting the parental melt was alkalic to shoshonitic. Low Cs concentrations, coupled with high Rb, Ba, and Nb, in MIs indicate minimal crystal fractionation of a near-primitive, mantle-derived composition. In contrast, whole-rock data show lower alkali contents (4.0 wt.%  $\text{K}_2\text{O}$ ) and have a subalkalic affinity, suggesting crustal contamination or alteration obscured the primitive magmatic signature.

A new, precise U-Pb zircon age constrains the felsic magmatism and porphyry-style mineralization at Jogran to the period of maximum lithospheric weakening/crustal thinning during the shift from extensional tectonics to thermal subsidence in the late stages of the MRS. This study suggests that early partitioning of metals and sulfur into magmatic fluids played a key role in ore formation. However, the conditions required remain ambiguous, as the tectonic environment at Jogran differs markedly from the subduction-related settings upon which most porphyry models are based. Porphyry deposits are increasingly recognised across a broader range of tectonic settings (e.g., southeast China [Richards, 2021]; and central Europe [Drew, 2006]). Jogran highlights the potential for porphyry-style mineralisation in non-subduction tectonic contexts and underscores the need to better understand metallogenic pathways beyond the traditional subduction models.

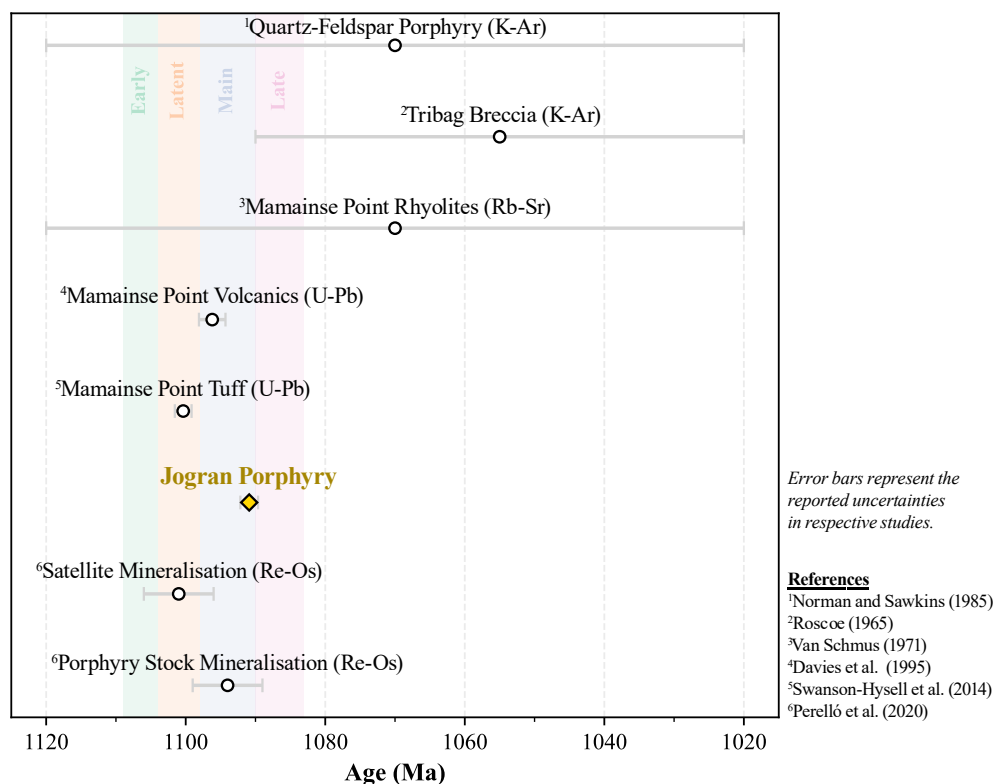


**Figure 1:** New U-Pb zircon age ( $1090.90 \pm 1.27$  Ma) for the Jogran porphyry (diamond), published age data (circles) and MRS stages defined by Woodruff et al., (2020) – Early (green), 1109–1104 Ma; Latent (orange), 1104–1098 Ma; Main (blue), 1098–1090 Ma; and Late (purple), 1090–1083 Ma.

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## Evaluating Ni in Olivine as a Prospectivity Indicator for Magmatic Ni-Cu-(PGE) Deposits: A Preliminary Study from the Midcontinent Rift System.

TOLLEY, James<sup>1</sup>, HOLLINGS, Pete<sup>1</sup>, MEXIA DURAN, Kevin<sup>1</sup> and HARDING, Myles<sup>1</sup>

<sup>1</sup>*Department of Geology, Lakehead University, 955 Oliver Road, Thunder Bay, ON P7B 5E1, Canada.*

Nickel content of olivine [(Mg,Fe)<sub>2</sub>SiO<sub>4</sub>] can serve as an important petrogenetic marker in mafic igneous systems. Nickel's concentration in olivine is controlled by several factors, including: (1) the Ni content of the parental magma; (2) the partition coefficient of Ni between olivine and the silicate melt; and (3) variable parameters such as temperature, pressure and *f*O<sub>2</sub> of the melt (Li *et al.*, 2007). More recently, Ni content in olivine has been studied as a potential fertility indicator for magmatic Ni-Cu sulfide deposits as well as providing information about the original composition of the magma. Olivine crystallizing from sulfide-saturated magmas will exhibit lower Ni contents relative to olivine crystallized from sulfide-undersaturated melts. This premise was assessed by Barnes *et al.* (2023) across Ni-Cu-(PGE) deposits globally, but there was a notable paucity of olivine data from Ni-Cu deposits within the Midcontinent Rift System (MRS).

This study presents 700 new electron probe microanalyses (EPMA) of Ni and other major elements in olivine from five magmatic Ni-Cu-(PGE) deposits in the MRS: Sunday Lake, Steepledge, Escape, Current and Hele. These data have been integrated with published datasets from the mineralised Seagull, Eagle and East Eagle intrusions to produce the first regional-scale dataset of olivine chemistry from the MRS. Curation of this data aims to assess: (1) the deposit scale variability of olivine chemistry across the MRS; (2) the utility of Ni in olivine as a regional prospectivity indicator for Ni-Cu deposits within the MRS; and (3) the implications for primary melt evolution across the MRS.

Preliminary results show that olivine forsterite (Fo) contents (i.e., 100\*Mg/[Mg+Fe<sub>total</sub>], mol %) range from Fo72.5-85 across most intrusions, except for the Hele intrusion, which has a much wider range (Fo44.0-82.5; Fig. 1). Across the entire dataset, Ni concentrations in olivine vary significantly (600-2500 ppm) and generally increase with higher Fo values. The range of Ni in olivine values can vary up to 1000 ppm from a single deposit, over a narrow Fo range (e.g., Current Intrusion – Fo79.7-81.7). Furthermore, concentric zoning between Mg-rich cores relative to the Mg-depleted rims is frequently observed – most notably at Eagle East, where an average core analysis displays Fo80 vs. average rim value of Fo77.

This preliminary compilation of olivine compositions across the MRS both reveals the variability of olivine compositions within a single intrusive complex and highlights fractionation trends regionally. The integration of the MRS data with the global compilation of Barnes *et al.* (2023) highlights the similarities between the signatures of unmineralized and mineralized intrusions and that there is no universal evidence for consistent Ni depletion in olivine from mineralised deposits. Placing the MRS olivine data within the context of other Ni-Cu-(PGE) systems may elucidate previously unrecognized potential within the MRS, and similarly these data can contribute to the global understanding of magmatic processes that culminate in economically viable deposits.

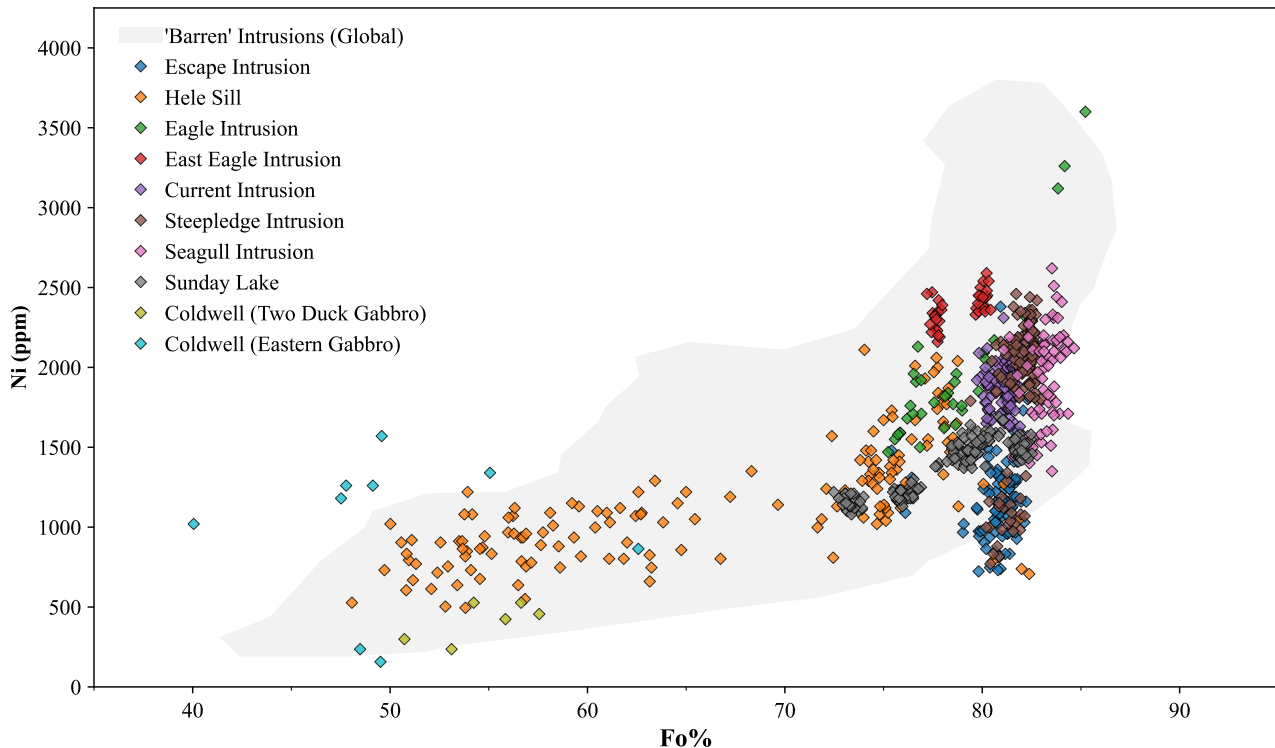


**Figure 1:** *Ni concentrations (ppm) in olivine as a function of forsterite content (Fo#) from a suite of mafic-ultramafic Ni-Cu intrusions located in the Midcontinent Rift System. Grey field denotes the global array of ‘barren’ intrusions as defined by Barnes et al. (2023). Published datasets comprise: (1) Eagle and East Eagle Intrusion – Ding et al. (2010); (2) Seagull Intrusion – Heggie (2005); (3) Coldwell, Two Duck Gabbro – Good (1992); (4) Coldwell, Eastern Gabbro – Shaw (1997).*

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## Origin of magnetic black sand found on the south Shore of Lake Superior

Verhoeven, J.D<sup>1</sup>., and Zowada, Tim<sup>2</sup>

*1 Iowa State University, Emeritus Prof., Iowa State University, Levering MI 49755, [jver@iastate.edu](mailto:jver@iastate.edu),*

*2 Custom Knifemaker, Boyne Falls, MI, [timzowada@gmail.com](mailto:timzowada@gmail.com)*

Many of the beaches on the shores of Lake Superior contain black sand which is magnetic. This sand can be smelted into iron using the ancient bloomery process which produces small chunks of iron called blooms. They consist of iron containing a low level of carbon. The chunk of iron is filled with cavities containing remnant slag produced in the smelting process. Recent experiments [1] have shown that often but not always the resultant iron of the blooms contain significantly levels of Ti and that one of the microconstituents in the slag is the mineral ulvöspinel. The authors of [1] had assumed that the magnetic black sand came from erosion of banded hematite-magnetite iron formations (BIF) which are the source of the iron mined in the Lake Superior region. Finding Ti in some of the blooms shows that there is likely an alternate source of the iron in the black sands, namely the Fe–Ti oxide-bearing ultramafic intrusions (OUIs) deposited in the lake bottom from the 1.1Ga Midcontinent Rift (MCR) that runs through the lake region. This talk presents a comparison of the composition of the ulvöspinel constituent found in bloom slags of black sand smelts with the composition of the ulvöspinel constituents found in a recent study [2] of drillings from the Coldwell Complex region located at the north central region of Lake Superior which contain Fe-Ti magnetite-ilmenite intergrow deposits from the MCR. The results present strong evidence that the some of the magnetic black sand on Lake Superior's shores comes from source rocks of MCR deposits in the Coldwell Complex and some from BIF deposits in the lake bottom. Additional evidence that the Fe-Ti source rock is the Coldwell Complex is that the location of the black sand used in the study is in the same region of the south shore of Lake Superior near White Fish Point where yooperlite rocks have been found. Literature data [3] shows that the source rock of the yooperlite is the Coldwell Complex.

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## **Zircon Petrochronology of the Eau Claire Volcanic Complex in the Marshfield Terrane of the Penokean Orogen, Northcentral Wisconsin**

**VICKERS, Lyndsie A.<sup>1</sup>, LODGE, Robert W.D.<sup>1</sup>**

<sup>1</sup>*Department of Geology and Environmental Sciences, University of Wisconsin-Eau Claire, Eau Claire, WI 54701 USA*

The Eau Claire Volcanic Complex (ECVC) serves as a type locality for Penokean-age magmatism and volcanism associated with the Marshfield terrane in the Penokean Orogeny (Figure 1A). This volcanic event is central to tectonic models that describe the collision of the Pembine-Wausau oceanic arc terrane and Archean crustal fragments of the Marshfield terrane with the southern margin of the Superior Craton (Shultz and Cannon 2007). A defining feature of these models is the proposed "double" subduction zone system, which is thought to have overprinted the Archean Marshfield terrane with younger Penokean volcanism and magmatism during ocean closure. Newer tectonic models suggesting accordion-like tectonics (Zi et al, 2022) still rely on historic interpretations of the ECVC where only physical outcrop descriptions in the literature (Myers et al, 1980). Despite its significance, the ECVC has remained understudied due to extensive Paleozoic and Quaternary cover which obscures outcrops and little mineral exploration and drilling. To address these challenges, this study focused on remote outcrops of the ECVC along the Eau Claire River in Wisconsin, aiming to better constrain tectonic models and clarify terrane boundaries in the southern Penokean Orogen.

Field mapping yielded samples that were processed to isolate zircon grains for U/Pb radiometric dating and petrochronological analyses. These zircons were analyzed using a Laser Ablation Inductively Coupled Plasma Mass Spectrometer (LA-ICP-MS) at Laurentian University, providing the only modern geochronological and petrochronological data (U/Pb, Lu/Hf, zircon trace elements) from this region in the orogen. The results challenge long-standing interpretations of the area's stratigraphy. Rocks previously classified as Paleoproterozoic volcanic units have Archean U/Pb ages and are now redefined as part of an Archean greenstone belt, significantly altering the geological narrative of the region. This study confirmed the presence of Paleoproterozoic intrusions (Figure 1C), but Lu-Hf isotopic analyses revealed that magmas did not have isotopic inheritance from the Archean basement (Figure 1D). This suggests the Paleoproterozoic magmas are in structural contact with Archean rocks. Additionally, Paleoproterozoic metasedimentary samples exhibited a diverse array of sedimentary sources (Figure 1-B), including Penokean, Marshfield, and a 2.2 Ga provenance, hinting at potential links to the Chocoy and Huronian groups which are continental rift assemblages formed during the breakup of an Archean supercontinent (Shultz & Cannon, 2007).

As the first comprehensive petrochronological dataset from the Penokean Orogen, this study not only redefines the age and origin of key outcrops but also shows the complexity of the region's tectonic and magmatic evolution. The discovery of previously unrecognized Archean basement rocks necessitates a reassessment of regional stratigraphy, particularly for classic outcrops historically attributed to Paleoproterozoic activity. Furthermore, the potential connection between the Marshfield terrane's sedimentary sources and those of the Superior Craton's rift assemblages raises questions about the terrane's origins, suggesting it may represent a southernmost fragment of the Superior Craton.

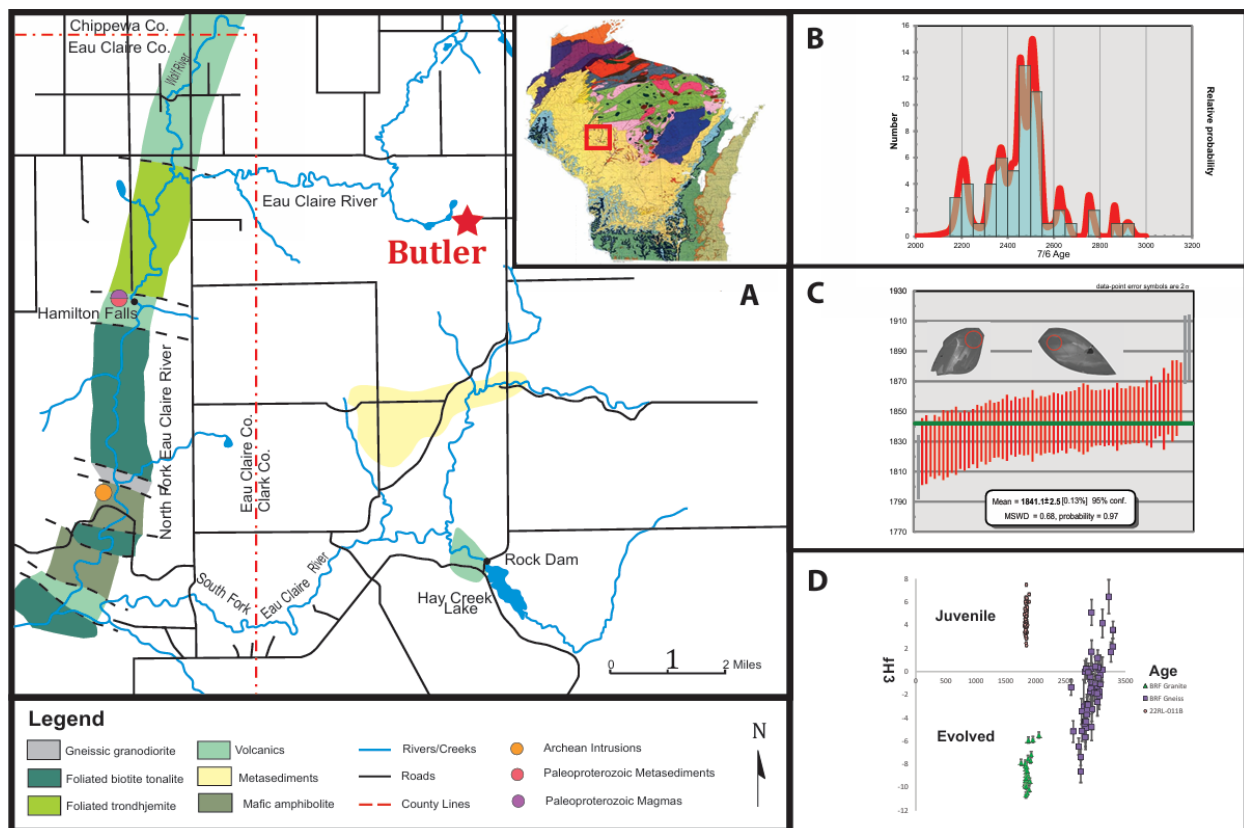


**Figure 1:** (A) Geologic map of the North Fork of the Eau Claire River adapted from Brown (1988). (B) Histogram displaying the distribution of zircon ages from a metasedimentary sample (C) Weighted mean diagram for intrusive sample showing a uniform range of zircon  $^{207}\text{Pb}/^{206}\text{Pb}$  ages. Grey bars represent outliers and were excluded from age calculation. (D)  $\text{EHf}_{(i)}$  versus  $^{207}\text{Pb}/^{206}\text{Pb}$  age comparing ECVC intrusion to other Penokean intrusions in the Marshfield Terrane (Weber et al., 2023).

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## Geospatial Learning Resources to Explore Relationships with Keweenaw Geology

VYE, Erika<sup>1</sup>, and LIZZADRO-MCPHERSON, Daniel<sup>2</sup>

<sup>1</sup>Great Lakes Research Center, Michigan Technological University, 1400 Townsend Drive, Houghton, MI, 49931, United States

<sup>2</sup>Geospatial Research Facility, Michigan Technological University, 1400 Townsend Drive, Houghton, MI, 49931, United States

The globally significant geologic processes and features of the Keweenaw have fostered relationships with land and water for millennia. We have created three geospatial, digital resources that express the deep relationships between the underpinning geology and the scientific, educational, cultural, economic, and aesthetic significance of publicly accessible geosites in the Keweenaw region. These geospatial resources serve as living databases that will evolve over time in order to support formal and informal learners in understanding the fundamental role geology plays in our varied relationships with land and water. All resources are hosted and shared publicly on the Geospatial Research Facilities' Enterprise Geospatial Research Portal at Michigan Technological University.

1) **The Keweenaw Coastal Geoheritage StoryMap** was created as a teaching and learning resource for local K-12 educators to explore the rock types of the Keweenaw at geosites along the shores of Lake Superior (Fig. 1). This resource: a) provides an overview of the main lithologies in the Keweenaw region, b) shares where federal, state, local government, and nonprofit organizations are working to preserve the rich geologic landscape and fragile wetlands of the Keweenaw, and c) provides a virtual learning experience to explore over 30 geologically significant sites along Lake Superior (Lizzadro-McPherson & Vye, 2023).

2) **The Keweenaw Geoheritage Geoatlas** is a knowledge directed exploration geospatial data hub that integrates physiographic landscape-wide feature coverages with a variety of downloadable GIS datasets. The repository of maps and data articulate the geoheritage of the region; the data hub supports educators, students, the scientific community, local tourist entities, land use planners, and the broader public in learning more about specific geosites in the Keweenaw region (Cowling, et al., 2024).

3) **The Keweenaw Geoheritage geodatabase and web-viewer** provide an innovative way of exploring the relationships between the bedrock geology and how this influences current and future education, conservation, and sustainable economic development initiatives in the Keweenaw region (Fig. 2). Each site expresses: a) a brief description of how the site contributes to the rich geoheritage of the Keweenaw, b) a 360-photo, and c) a description of the scientific (specific to the geologic phenomena), educational, cultural, economic, and aesthetic significance of the site (Lizzadro-McPherson & Vye, 2024).

These resources are intended to support the co-stewardship of cultural heritage, restoration of legacy mining sites, conservation issues, and the development of sustainable economic opportunities based on the region's globally significant geologic underpinnings. Further, they serve as the foundation for an evolving community participatory geoheritage mapping project in the Keweenaw. Through innovative, interactive geospatial resources we aspire to engage the broader public in sharing and exploring their relationships with the Keweenaw landscape (e.g. stories, valued geosites, photos, and curiosities).

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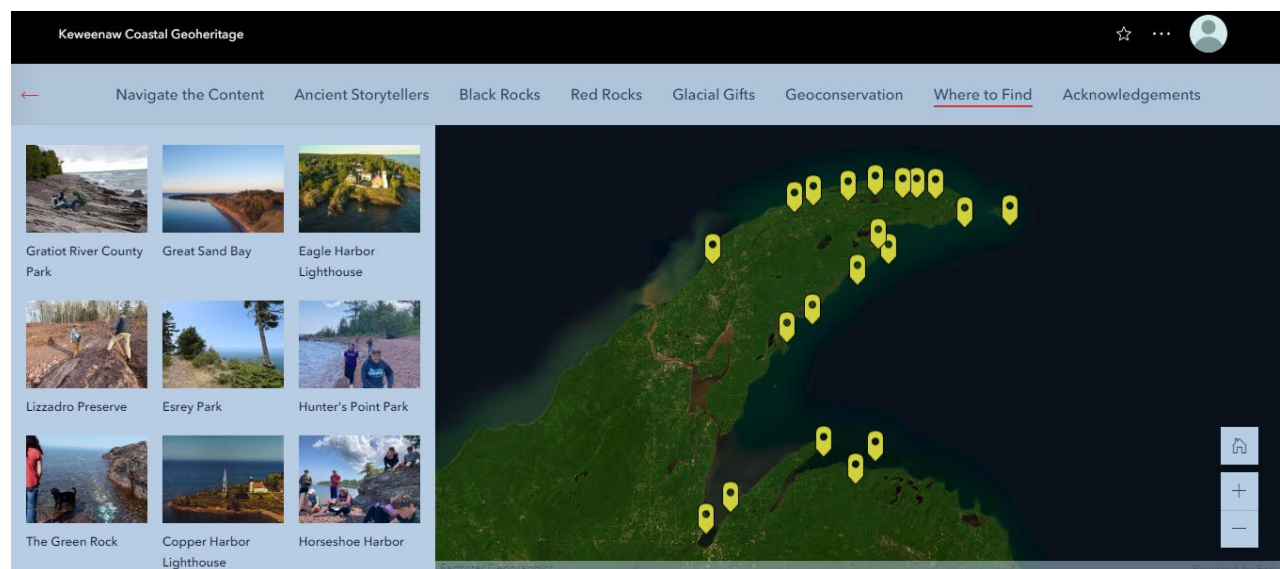


Fig. 1: Keweenaw Coastal Geoheritage StoryMap

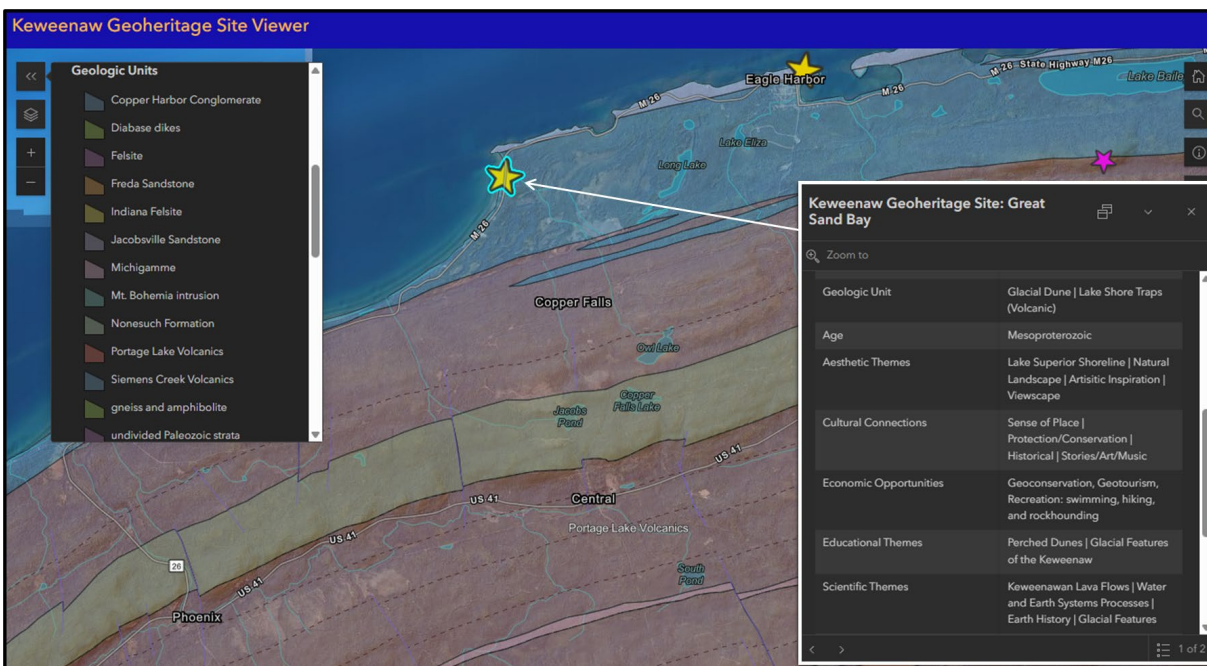


Fig. 2: Keweenaw Geoheritage Viewer

## **Battle between the bands: competitive precipitations lead to bands in banded iron formations**

**Xu, Huifang, and Zhou, Tianyu**

*Department of Geoscience, University of Wisconsin–Madison, Madison, WI 53706, USA*

Banded iron formations (BIFs) are massive chemical deposits composed of alternating layers of chert and iron-rich minerals (such as hematite, magnetite and siderite), with three scales of bandings: microbands, mesobands (1 mm - 10 cm) and macrobands. Their abundance in the Archaean/early Proterozoic era and their absence thereafter suggest that chemical conditions and iron transport pathways on the early Earth surface were different from those after 1.7 billion years ago. Thermodynamic calculations show that Fe-silicate metal complex can be generated by hydrothermal leaching of low-Al oceanic crustal rocks such as komatiites, which suggest that the presence of low-Al ultramafic rocks (for example, komatiitic rocks) in the early oceanic crust were the reason for both the formation of BIFs and their abundance in the Archaean/early Proterozoic era (Wang et al., 2009). This is consistent with the findings that the ages of komatiites are correlated strongly, at the 99% confidence level, with the ages of BIFs (Isley and Abbott, 1999).

We used the PHREEQC geochemical modeling package was used to test the chemical reactions that may have led to the banding pattern in the BIFs based on competitive precipitation of ferrihydrite (precursor of hematite and magnetite) and silica gel (precursor of chert) (Zhou et al., 2024). After aqueous ferrous silicate decomposition in O<sub>2</sub>-sufficient condition ( $pO_2 \geq 10^{-4}$ ), the faster Fe<sup>2+</sup> oxidation and precipitation rate led to Fe-rich layer preceding Si-rich layer with ferrihydrite and amorphous silica as the precursor to the hematite and quartz, respectively. Episodic Fe(H<sub>3</sub>SiO<sub>4</sub>)<sub>2</sub> input resulted in successive cycles of layering (Fig. 1). O<sub>2</sub>-deficient environments ( $pO_2 < 10^{-4}$ ) results in jaspilite (no bands). The kinetic model also works well for the formation of siderite bands under O<sub>2</sub>-deficient environments when  $pCO_2$  is high. In summary, the precipitation process model proposed in this study offers an alternative abiotic explanation for the formation of distinct bands within the BIFs.

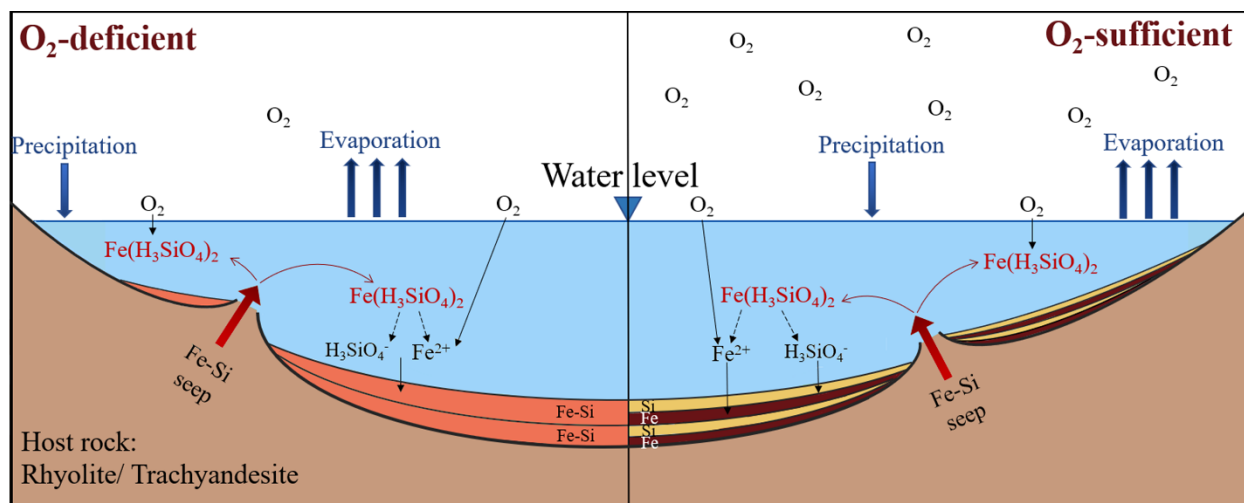


Figure 1: Schematic depositional model of felsic volcanism associated BIF-like Iron Formations under different surface oxygen levels in a shallow hot spring lake ( $O_2$ -deficient:  $pO_2 < 10^{-4}$ ;  $O_2$ -sufficient:  $pO_2 \geq 10^{-4}$ ). When the  $O_2$  level is high, the mix of aerobic lake water and  $Fe(H_3SiO_4)_2$ -bearing spring fluid leads to the ferrihydrite-rich layer and amorphous silica-rich layer precipitating successively. But ferrihydrite and silica coprecipitate when  $O_2$  is deficient and there is no layering. The ferrihydrite-rich layer would convert to hematite-rich layer and amorphous silica-rich layer transforms into Si-rich layer. The surface water level is regulated by precipitation, evaporation and seepage from surrounding rock without visible inflow or outflow. DOI: [10.1016/j.chemgeo.2024.122091](https://doi.org/10.1016/j.chemgeo.2024.122091)

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**Broadly coeval but migrating deformation, plutonism and deposition in the northeastern Superior Province, Québec: evidence of hot accretionary orogeny and oroclinal folding in the late Archean?**

**ŽÁK, Jiří<sup>1, 2</sup>, TOMEK, Filip<sup>1, 2</sup>, KACHLÍK, Václav<sup>1</sup>, VACEK, František<sup>1, 3</sup>, SVOJTKA, Martin<sup>2</sup>, and ACKERMAN, Lukáš<sup>2</sup>**

<sup>1</sup> *Institute of Geology and Paleontology, Faculty of Science, Charles University, Albertov 6, Prague, 12843, Czech Republic* <sup>2</sup> *Institute of Geology of the Czech Academy of Sciences, Rozvojová 269, Prague, 16500, Czech Republic* <sup>3</sup> *Czech Geological Survey, Klárov 3, Prague, 11821, Czech Republic*

The James Bay Road in Québec provides a unique crustal-scale transect across several principal lithotectonic belts of the northeastern Superior Province. From north to south, these belts are Bienville (plutonic), La Grande ('gray' gneisses, metaplutonic), Opinaca–Némiscau (metasedimentary), and Opatica (mostly volcano-plutonic). This assemblage has been controversially interpreted to record non-plate vertical tectonics driven by mantle plume activity or as resulting from the step-wise accretion of these belts to the northerly proto-cratonic core. We present here new structural and anisotropy of magnetic susceptibility (AMS) data from all the units along the James Bay Road transect. The data indicate a multistage fabric evolution: (1) an early fabric F1 is preserved only in isolated domains across the La Grande and Opinaca belts and is at a high angle to boundaries between the individual belts; (2) the F2 fabric seems to record a progressive reorientation (folding) towards an E–W direction; (3) the regionally dominant F3 fabric indicates regional NNE–SSW shortening across all units and is coeval with pluton emplacement and anatexis; (4) the last major ductile event is represented by localized dextral shear zones. The AMS indicates that magnetic foliations in general match well the mesoscopic foliations, whereas magnetic lineations vary from steeply plunging to subhorizontal, interpreted as recording a transition from vertical stretching during folding to horizontal stretching during shearing. The latter interpretation is further supported by a more detailed analysis of the ca. 2712–2697 Ma Radisson pluton, which is a syntectonic intrusion at the Bienville–La Grande boundary. Its magmatic to solid-state fabrics analyzed through the AMS also suggest a strain evolution from vertical magma stretching during regional shortening overprinted by later dextral shearing. In conjunction with the previously published U–Pb geochronology, the structural data suggest a short time span and north-to-south migration of plutonism, deposition, and contractional/transpressional deformation, altogether favoring a modern-style plate tectonics operating in the NE Superior Province in the late Archean. Furthermore, the relict F1 and F2 fabrics overprinted by F3 are interpreted as being compatible with changing block/microplate convergence vectors and crustal-scale folding of the outboard La Grande and Opinaca–Némiscau belts. In conclusion, the northeastern Superior Province may have been assembled as large, hot accretionary supra-subduction orogen, oroclinally folded, and finally dextrally sheared. Were this interpretation correct, a key question arises what was the geodynamic cause and mode of the oroclinal folding, whether with or without hard collision, taking the Alaskan terrane wreck or Mongolian orocline as prime examples, respectively.