

# 68<sup>th</sup> ANNUAL MEETING

Sudbury, Ontario — May 10-11, 2022

## INSTITUTE ON LAKE SUPERIOR GEOLOGY

### Part 1 — Program and Abstracts



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**68<sup>th</sup> ANNUAL MEETING**

# **INSTITUTE ON LAKE SUPERIOR GEOLOGY**

**May 10-11, 2022**

**Sudbury, Ontario**

**HOSTED BY**

**Michael Easton and Wouter Bleeker Co-Chairs**

**Ontario Geological Survey and Geological Survey of Canada**

**Proceedings - Volume 68**

**Part 1 – Program and Abstracts**

**Compiled and edited by Michael Easton**

Cover Photos. Left — Cross-bedded Mississagi Formation, Elliot Lake. Middle — Shatter cones in Mississagi Formation sandstone, Ramsey Lake Road Sudbury. Right — Fold in quartzofeldspathic gneiss immediately south of the Grenville Front, Stinson.



# **68<sup>th</sup> INSTITUTE ON LAKE SUPERIOR GEOLOGY**

## **VOLUME 68 CONSISTS OF:**

### **PART 1: PROGRAM AND ABSTRACTS**

### **PART 2: FIELD TRIP GUIDEBOOK**

**Trip 1:** A TRAVERSE ACROSS THE SUDBURY IMPACT STRUCTURE

**Trip 2:** GEOLOGY OF THE GRENVILLE FRONT IN THE SUDBURY AREA

**Trip 3:** MAGMATISM AND BRECCIATION IN THE FOOTWALL ROCKS  
IN THE SOUTHWESTERN SUDBURY STRUCTURE

**Trip 4:** AN OVERVIEW OF THE GEOLOGY OF THE SUDBURY STRUCTURE

**Trip 5:** A CROSS-SECTION THROUGH THE HURONIAN SUPERGROUP AT  
ELLIOT LAKE, ONTARIO

### **Reference to material in Part 1 should follow the example below:**

Miller, Jim, Flank, S. Djon, L., Brown, J. and Nikkila, D. 2022. Lithostratigraphy, mineralization, and petrogenesis of the MCR-related Sunday Lake Intrusion, NW Ontario. *in* Easton, R.M. (Ed.), Institute on Lake Superior Geology Proceedings, 68<sup>th</sup> Annual Meeting, Sudbury, Ontario, Part 1 - Abstracts and Proceedings. v.68, part 1, p.40-41.

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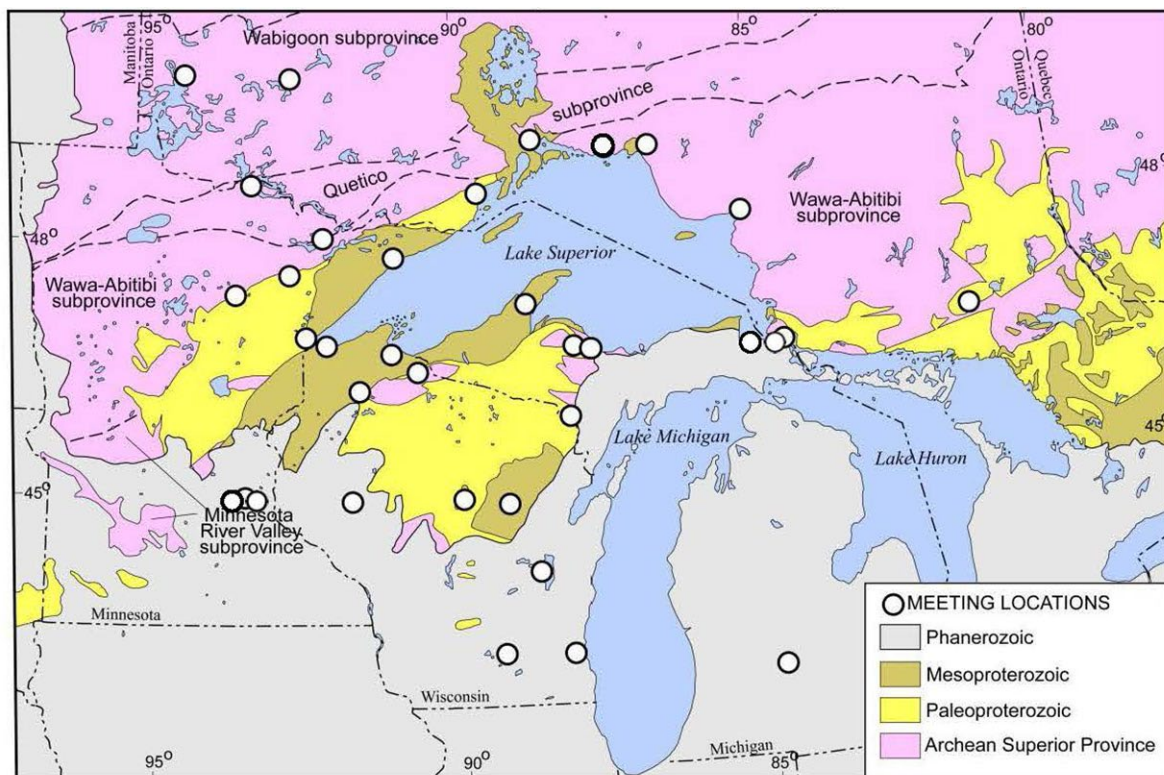


## **Part 1: Program and Abstracts**

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## Institutes on Lake Superior Geology, 1955-2022



| #  | Date | Place                      | Chairs                      |
|----|------|----------------------------|-----------------------------|
| 1  | 1955 | Minneapolis, Minnesota     | C.E. Dutton                 |
| 2  | 1956 | Houghton, Michigan         | A.K. Snelgrove              |
| 3  | 1957 | East Lansing, Michigan     | B.T. Sandefur               |
| 4  | 1958 | Duluth, Minnesota          | R.W. Marsden                |
| 5  | 1959 | Minneapolis, Minnesota     | G.M. Schwartz & C. Craddock |
| 6  | 1960 | Madison, Wisconsin         | E.N. Cameron                |
| 7  | 1961 | Port Arthur, Ontario       | E.G. Pye                    |
| 8  | 1962 | Houghton, Michigan         | A.K. Snelgrove              |
| 9  | 1963 | Duluth, Minnesota          | H. Lepp                     |
| 10 | 1964 | Ishpeming, Michigan        | A.T. Broderick              |
| 11 | 1965 | St. Paul, Minnesota        | P.K. Sims & R.K. Hogberg    |
| 12 | 1966 | Sault Ste. Marie, Michigan | R.W. White                  |
| 13 | 1967 | East Lansing, Michigan     | W.J. Hinze                  |
| 14 | 1968 | Superior, Wisconsin        | A.B. Dickas                 |
| 15 | 1969 | Oshkosh, Wisconsin         | G.L. LaBerge                |
| 16 | 1970 | Thunder Bay, Ontario       | M.W. Bartley & E. Mercy     |
| 17 | 1971 | Duluth, Minnesota          | D.M. Davidson               |
| 18 | 1972 | Houghton, Michigan         | J. Kalliokoski              |
| 19 | 1973 | Madison, Wisconsin         | M.E. Ostrom                 |
| 20 | 1974 | Sault Ste. Marie, Ontario  | P.E. Giblin                 |
| 21 | 1975 | Marquette, Michigan        | J.D. Hughes                 |
| 22 | 1976 | St. Paul, Minnesota        | M. Walton                   |
| 23 | 1977 | Thunder Bay, Ontario       | M.M. Kehlenbeck             |

| <b>#</b> | <b>Date</b> | <b>Place</b>                   | <b>Chairs</b>                                            |
|----------|-------------|--------------------------------|----------------------------------------------------------|
| 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                      |
| 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                                 |

## **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. Kalliokosi, 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 medallists 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 medallist, and have one medal engraved appropriately for presentation at the next meeting of the Institute.
- 5) It is recommended that the Institute set aside annually from whatever sources, such funds as will be required to support the continuing costs of this award.

## **Nominating Procedures**

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

## **Selection Guidelines**

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

## **Goldich Medalists**

|      |                      |      |                                             |      |                      |
|------|----------------------|------|---------------------------------------------|------|----------------------|
| 1979 | Samuel S. Goldich    | 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                                   |      |                      |
| 1987 | Henry H. Halls       | 2006 | Michael G. Mudrey                           |      |                      |
| 1988 | Walter S. White      | 2007 | Joseph Mancuso                              |      |                      |
| 1989 | Jorma Kalliokoski    | 2008 | Theodore J. Bornhorst                       |      |                      |
| 1990 | Kenneth C. Card      | 2009 | L. Gordon Medaris, Jr                       |      |                      |
| 1991 | William Hinze        | 2010 | William D. Addison &<br>Gregory R. Brumpton |      |                      |
| 1992 | William F. Cannon    | 2011 | Dean M. Rossell                             |      |                      |
| 1993 | Donald W. Davis      | 2012 | James D. Miller                             |      |                      |
| 1994 | Cedric Iverson       | 2013 | Tom Waggoner                                |      |                      |
| 1995 | Gene La Berge        | 2014 | Laurel Woodruff                             |      |                      |
| 1996 | David L. Southwick   | 2015 | Rodney J. Ikola                             |      |                      |
| 1997 | Ronald P. Sage       |      |                                             |      |                      |

**2022 GOLDICH MEDAL RECIPIENT**

**Terrence J. Boerboom**

## **Goldich Medal Committee**

Serving through the meeting year shown in parentheses.

Dan England (2017-2022) Eveleth Fee Office (Committee Chair)

Dorothy Campbell (2020-2024) Ontario Geological Survey

Steve Kissin (2018-2023) Lakehead University

*Terms of the committee members were extended 2 years because of the cancelation of the 2020 meeting and the logistical difficulties of voting during the 2021 virtual meeting.*

## **Citation for the Goldich Medal Recipient to Terrence J. Boerboom**



I have the great pleasure of nominating Terrence J. Boerboom for the Sam Goldich Medal.

Terry got a geology degree from the University of Minnesota-Morris in 1982; and a Masters degree from the University of Minnesota-Duluth in 1987. His thesis dealt with tourmalinites, nelsonites, and related Paleoproterozoic rocks from drill cores in central Minnesota. He has worked for the Minerals Division of the Minnesota Department of Natural Resources, Noranda Exploration Company, and has spent the last 35 years working for the Minnesota Geological Survey.

Terry epitomizes the Goldich award criteria; “contributions to Lake Superior geology and to the Institute.” There can be little more substantive than the huge amount of basic geological knowledge he has produced from his excellent and extensive geologic mapping in northeastern and east-central Minnesota.

Working for the Minnesota Geological Survey, he has published at least 33 bedrock geologic maps and co-authored ten others. Mainly located in the Midcontinent Rift and the Animikie Basin—Penokeyan Orogen districts, these publications illustrate his unmatched energy and skills as a field geologist. In much of this area, he has followed in the footsteps of my field reconnaissance work, but taking many, many more footsteps of his own. He is a meticulous observer of outcrops and interpreter of what they have to show us, integrating available geophysical, geochemical, and petrographic information in his interpretations. He has much improved our understanding of the structure, stratigraphy, and geologic history of the region. Now using the magic of LIDAR imagery, he searches out rock exposures in the puckerbrush that no-one would otherwise suspect existed.

Terry has also been outstanding in sharing his geologic mapping results with others, in the forms of presentations at ILSG meetings (at least 42 that I know of), GSA meetings, leading and co-leading many field trips, and producing guidebooks. He recently retired from the Minnesota Geological Survey after 35 years, but returned part-time to contribute his knowledge and experience to ongoing mapping and mappers.

Terry has also collaborated with many others, as author or co-author of research papers in several peer-reviewed journals, in the fields of geochronology, tectonics, geochemistry, saprolite interpretation, and paleomagnetism. As someone who has collaborated with Terry on many mapping projects along Minnesota's North Shore, I can personally vouch for his petrographic skills, his energy, his perseverance and enthusiasm, and basic likability. It has been a great pleasure to work with him.

To sum up, Terry richly deserves the Sam Goldich medal.

*Submitted by John C. Green, Professor Emeritus  
Department of Earth and Environmental Sciences  
University of Minnesota–Duluth  
Duluth, MN 55804*

## **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 inception of the institute in 1955. Biographical sketches of those pioneers will be presented at future annual meetings so that all might 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 summarise the contribution of the nominee.
- 2) The Organising 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)

## **Nomination for Thomas Leslie Tanton Pioneer of Lake Superior Geology**



Thomas (T.L.) Tanton (1890-1971) was an eminent geologist who served in the Geological Survey of Canada (GSC) for over 40 years. A major focus of his work was the Precambrian geology and mineral resources of the Lake Superior region. He received his BA and MA degrees from the University of Toronto and his PhD from the University of Wisconsin under the guidance of C.K. Leith. Joining the GSC in 1915, he made a lasting contribution to the geology of Canada during his career, as represented in part by more than 40 reports, maps, and papers, many of them focusing on the geology of northwestern Ontario.

Dr. Tanton's early work with the GSC involved reconnaissance surveys in northern Ontario. Working from bases on the railways, he delineated greenstone belts and other prospective areas. As an enthusiastic field geologist, he was a popular public servant who gave expert advice freely to prospectors, developers and others. Early reconnaissance work was followed

by more systematic regional studies, particularly north and west of Lake Superior. A large part of this detailed, regional work culminated in several maps and reports, published from 1930 to 1940 (see Appendix).

Dr. Tanton also made important contributions to the understanding of varied geological processes. He was involved with the debate on the age of the Couthiching series of rocks, studied liquid immiscibility in Keweenawan rhyolites, and postulated on the origin of the Steep Rock Lake iron ore deposits, for example.

He stimulated and encouraged those around him by his originality in approach and concepts, and his scientific peers and associates were challenged to re-examine accepted ideas and values. Dr. Tanton made a lasting contribution to the understanding of the geology of the Precambrian of Canada and particularly in many areas north and west of Lake Superior. He should merit consideration as a Pioneer of Lake Superior Geology.

*[modified after a Memorial written by Gordon Gross in 1971]*

Mark Smyk and Jim Miller

**APPENDIX: PERTINENT SELECTED PUBLICATIONS OF T.L. TANTON**

**1917**

Reconnaissance along Canadian Northern Railway between Gogama and Oba, Sudbury and Algoma Districts, Ontario; Geological Survey Canada, Summary Report, 1916, p.179-182.

**1918**

Canadian Northern Railway between Nipigon and Longuelac, northern Ontario; Geological Survey Canada, Summary Report, 1917, pt. E, p.1-6.

**1919**

The Canadian National Railways between Longuelac and Oba, northern Ontario: Geological Survey Canada, Summary Report, 1918, pt. E, p. 1-3.

**1920**

Shore of Lake Superior between Port Arthur and Nipigon; Geological Survey Canada, Summary Report, 1919, pt. E, p.1-7 (contains map 1811 – lead- and zinc-bearing veins, Dorion Township and vicinity, Thunder Bay district).

Silver Islet and vicinity; Transactions Canadian Mining Institute, v.23, p.402-418.

**1921**

Thunder Bay district, Ontario: Geological Survey Canada, Summary Report, 1920, pt. D, p.1-2.

Nipigon - Schreiber district, Ontario: Geological Survey Canada, Summary Report, 1920, pt. D, p.2-7.

**1922**

An exploration north of Thunder Bay, Ontario; Geological Survey Canada, Summary Report, 1921, pt. D, p.1-5.

**1923**

Palladium-bearing nickel deposit at Shebandowan Lake, Thunder Bay district, Ontario; Geological Survey Canada, Summary Report, 1922, pt. D, p.1-8.

Gold occurrence at Makwa, Sudbury district, Ontario; Geological Survey Canada, Summary Report, 1922, pt. D, p.9-12.

The effect of glaciation on prospecting for mineral deposits in the Laurentian Plateau; Geography Review, v.13.

**1924**

Iron formation at Gravel Lake, Thunder Bay district, Ontario; Geological Survey Canada, Summary Report, 1923, pt. CI, p.1-5.

**1925**

Eastern part of Matawin Iron Range, Thunder Bay district, Ontario; Geological Survey Canada, Summary Report, 1924, pt. C, p.1-27, with Map 2069.

Evidence of liquid immiscibility in a silicate magma, Agate Point, Ontario; reprinted Journal of Geology, v.33, no.6, p.629-641, including tables, map, photos.

**1926**

Recognition of the Couthiching near Steeprock Lake, Ontario; Royal Society of Canada, section IV, no.20, p.39.

**1927**

Mineral deposits of Steeprock Lake map area; Geological Survey Canada, Summary Report, 1925, pt. C, p.1-11.

Stratigraphy of the northern subprovince of the Lake Superior region; Geological Society of America, Bulletin, v.38, p.731-748.

**1931**

Fort William and Port Arthur, and Thunder Cape map areas, Thunder Bay district, Ontario; Geological Survey Canada, Memoir 167, with Maps 1902, 197A (surficial) and 276 A (see also Maps 198A, 203A, and 214A).

**1932**

Pearl (Ontario): *in* Manganese deposits of Canada Geological Survey Canada, Economic Geology Series, no. 12, p.102-104.

**1933**

Kenora sheet, Ontario: Geological Survey Canada, Map 266A, scale 1:506,880.

**1934**

Sturgeon River area, Thunder Bay district, Ontario: Geological Survey Canada, Map 312A, scale 1:126,720.

Little Long Lac area, Thunder Bay district, Ontario: Geological Survey Canada, Map 313A, scale 1:126,720.

**1935**

Copper - nickel occurrences in Pigeon River area, Ontario: Geological Survey Canada, Paper 35-1  
(see Maps 354A, 355A, and 356A).

**1936**

Mine Centre area, Rainy River district, Ontario: Geological Survey Canada, map 334A, scale 1:31,680.

Pigeon River area (sheet 1), Thunder Bay district, Ontario: Geological Survey Canada, map 354A, scale 1:63,360.

Pigeon River area (sheet 2), Thunder Bay district, Ontario: Geological Survey Canada, map 355A, scale 1:63,360.

Pigeon River area (sheet 3), Thunder Bay district, Ontario: Geological Survey Canada, map 356A, scale 1:63,360.

**1938**

Ignace sheet, southwest quarter, Kenora district, Ontario; Geological Survey Canada, Paper 38-13, scale 1:126,720  
(see Map 557A).

Shebandowan area, Thunder Bay district, Ontario; Geological Survey Canada, Map 338A, scale 1:63,360.

Quetico sheet (east half), Thunder Bay and Rainy River districts; Geological Survey Canada, Map 432A, scale  
1:253,440.

**1939**

Quetico (west half), Rainy River district, Ontario: Geological Survey Canada, Map 534A, scale 1:253,440.

**1941**

Origin of the hematite deposits at Steeprock Lake, Ontario; Royal Society of Canada, series 3, section 4, v.35,  
p.131-141.

Areas in the vicinity of Steeprock Lake, Rainy River district, Ontario (Summary account); Geological Survey  
Canada, Paper 41-13; scale 1:2,400 and 1:6,000.

**1946**

The iron ore at Steeprock Lake; Reprint from Royal Society of Canada, Transactions, series 3, section 4, v.40, 9p.

**1948**

New Helen Mine: in Structural geology of Canadian ore deposits: a symposium; Canadian Institute of Mining and  
Metallurgy, p.422-428.

Radioactive nodules in sediments of the Sibley series, Nipigon, Ontario; Royal Society of Canada, Transactions,  
series 3, section 4, v.42, p.69-75.

An occurrence of boron minerals at Silver Harbour, Lake Superior; Royal Society of Canada, Transactions, series  
3, section 4, May 1948, p.77-79.

## **In Memoriam**

### **Richard “Dick” Buchheit**



Richard (Dick) Buchheit, of Grand Marais, Minnesota, died June 23, 2021 at age 86. He was born September 18, 1934, in Minneapolis, to Frank and Lola Buchheit. He enjoyed playing football and basketball while in high school at St. Louis Park High School in St. Louis Park, Minnesota. He played football at Carleton College in Northfield, Minnesota, and was approached in November 1955 by the Chicago Cardinals Football Club to enter the 1956 National Football League draft. Instead, he pursued his Master's Degree at the University of Minnesota after earning his Bachelor of Science in Geology at Carleton College. He served in the Army Reserves until being discharged to start his career as an Exploration Geologist with the New Jersey Zinc Company. Dick was an avid "rock picker" whose profession took him into the remote bush country of Northern Canada, the red rocks of the Southwest, the coal mines of Pennsylvania, and ultimately the Land of Minnesota's 10,000 Lakes where he finished his career as the Owner and CEO of the Eveleth Fee Office in Eveleth, Minnesota, retiring in 2000. He was a talker and enjoyed sharing his knowledge with anyone who would listen. It was at the Happy Jack Uranium mine in Southeast Utah in 1961 where he met Nedetta Pinder. They were married March 4, 1962 and soon started their family. Many moves and three children later, they eventually settled into retirement, splitting their time between the Pinder homestead in Colorado and their lake home near Grand Marais. He continued to live in their lake home after Detta passed away in 2013 and only left this past April when he entered the North Shore Care Center because of health issues. Dick was preceded in death by his wife, father and mother, and his younger brother Paul. He is survived by sons Jon Buchheit, Scott (Cheryl) Buchheit, and daughter Sheila Buchheit, grandchildren Michaela (Sean) Trevithick, Zachary Buchheit, Matthew Buchheit, Trevor Wilson, and great-granddaughter Emilia Trevithick, as well as many nieces and nephews.

## **In Memoriam**

### **Ann Wilson**



Ann Wilson, a long-time ILSG organizer and supporter, passed away peacefully on November 1<sup>st</sup>, 2021. Ann had been diagnosed in 2018 with Alzheimer's and moved to be close to family in Hamilton, Ontario, leaving her much-loved home and career with the Ontario Geological Survey (OGS) in Timmins.

Ann completed her undergraduate studies at McMaster University and obtained her Master's degree in Geological Studies from Queens University. She spent over 30 years with the Resident Geologist Program of the OGS, working in a variety of roles, including positions as District Geologist in Wawa and Timmins, and most recently, as a Mineral Deposit Compilation Geoscientist. Ann made important contributions to the Land Use Geology program and was the lead author of the Procedural Guidelines for Provincially Significant Mineral Potential Mineral Resource Assessments.

Ann was also a keen supporter of the Institute on Lake Superior Geology, having Co-Chaired the 2006 and 2017 meetings in Sault. Ste. Marie and Wawa, respectively. Many ILSG members will remember Ann's work in documenting the unusual, Archean diamond-bearing rocks of the Wawa area. She carried out her work in a very efficient and no-nonsense fashion, traits that she was known for throughout her career.

## **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 annual banquet.

The following general criteria will be considered by the annual Chair, who is responsible for the selection:

- 1) The applicants must have active resident (undergraduate or graduate) student status at the time of the annual meeting of the Institute, certified by the department head.
- 2) Students who are the senior author on either an oral or poster paper will be given favored consideration.
- 3) It is desirable for two or more students to jointly request travel assistance.
- 4) In general, priority will be given to those in the Institute region who are farthest away from the meeting location.
- 5) Each travel award request shall be made in writing to the annual Chair, and should explain need, student and author status, and other significant details.

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 2021, the ILSG Board of Directors selected two students to be granted research funding of \$1000.00 each from the Joe Mancuso Student Research Fund. The awardees were:

### **Miles Harbury**

University of Wisconsin – Milwaukee

Department of Geosciences

TOPIC: *Determining the genetic origins of Paleoproterozoic diamictites using Anisotropy of Magnetic Susceptibility (AMS)*

### **Katherine Langfield**

Michigan Technological University,  
Department of Geological and Mining  
Engineering and Sciences, Houghton,  
MI, USA

TOPIC: *Slip Kinematics of the Hancock Fault in the Midcontinent Rift System, Keweenaw Peninsula, Michigan*

## **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.

## **Board of Directors**

Board appointment continues through the close of the meeting year shown in parentheses, or until a successor is selected.

*The terms of Board members were extended 2 years because of cancellation of the 2020 meeting, and the difficulties of virtual voting by the membership during the 2021 meeting.*

**Mark Smyk** (2019-2024) — Lakehead University

**Esther Stewart** (2018-2023) – Wisconsin Geological & Natural History Survey

**Anthony Pace** (2017-2022) — Ministry of Northern Development, Mines,  
Natural Resources and Forestry, Sault Ste Marie

**Pete Hollings** — Secretary (2019-2024) — Lakehead University

**Mark A. Jirsa** — Treasurer (2017-2022) — Minnesota Geological Survey

## **Field Trip Leaders and Guidebook Authors**

Field trips have been the mainstay of the ILSG since its inception 68 years ago. We want to give a special thanks to the field trip leaders and guidebook authors who volunteered their time and talent in carrying that tradition forward.

### **1) A Traverse across the Sudbury Impact Structure**

Wouter Bleeker – Geological Survey of Canada

Sandra Kamo – University of Toronto

Michael Leshner – Laurentian University

Henning Seibel – Laurentian University

### **2) Geology of the Grenville Front in the Sudbury area**

Michael Easton – Ontario Geological Survey

### **3) Magmatism and Brecciation in the Footwall Rocks in the southwestern Sudbury Structure**

Caroline Gordon - Ontario Geological Survey

Carol-Anne G  n  reux - Laurentian University & Terrane Geoscience Inc.

Brad Clarke - SPC Nickel Corporation

### **4) An overview of the geology of the Sudbury Structure**

Shirley P  loquin – Ontario Geological Survey

### **5) A cross-section through the Huronian Supergroup at Elliot Lake, Ontario**

Michael Easton – Ontario Geological Survey

with contributions from Gerry Bennett – Ontario Geological Survey retired

## **REPORT OF THE 67<sup>th</sup> ANNUAL (VIRTUAL) MEETING OF THE INSTITUTE ON LAKE SUPERIOR GEOLOGY**

With the global pandemic limiting travel and gathering, the ILSG Board of Directors decided to hold the 2021 meeting virtually. The meeting was Chaired by Mark Jirsa (Minnesota Geological Survey), Mark Smyk and Pete Hollings (Lakehead University) with support from the Lakehead University Technology Services Centre, particularly Blain Boyd and Shawn Hartviksen. The meeting consisted of four 3-hour Technical Sessions, one poster session, and an Awards Evening spread over two weeks (May 11<sup>th</sup>, 14<sup>th</sup>, 18<sup>th</sup>, 21<sup>st</sup>). A total of 313 people registered for the meeting to allow organizers to forward the Zoom link. There was no cost for registration, hence no income was generated. Attendance at individual sessions ranged from 130 to 150.

The Technical Sessions comprised 29 oral and seven poster presentations. Poster presenters gave 5-minute synopses prior to entertaining questions and discussion in their respective, virtual breakout rooms. Proceedings Volume 67 was published (digitally) only as Part 1 – Program and Abstracts, compiled and edited by Mark Jirsa (MGS). It contains published abstracts for 30 oral (one presentation was cancelled) and 7 poster presentations. No field trips were offered (and thus, no Part 2 Field Trip Guidebook was issued). No corporate sponsorships were solicited. Student paper and travel awards were not given out at this meeting. Although the Board of Directors met virtually in 2020 and 2021, they did not meet during the meeting. It was agreed that the membership of the Board and of the Goldich Medal Committee would remain the same until 2022.

The Awards Evening was held on Friday, May 21<sup>st</sup>. It featured the awarding of the 2021 Goldich Medal to Allan (“Al”) MacTavish for his many decades as an exploration geologist, mapper, and proud ILSG supporter. Al’s citation was read by Mark Puumala of the Ontario Geological Survey (OGS). A presentation was provided by Michael Easton (OGS) to outline plans for the 68<sup>th</sup> ILSG meeting in Sudbury in 2022. This meeting will be Co-Chaired by Wouter Bleeker (Geological Survey of Canada). Peter Hinz provided details of a proposed field trip to Iceland in July-August of 2022. As part of ILSG’s *Honouring the Pioneers of Lake Superior Geology*, Jim Miller (MGS, Retired) gave a presentation on Newton Horace Winchell, the first Director of the Geological and Natural History Survey of Minnesota. Jim described some of Winchell’s remarkable professional life. He was then joined by Sue Leaf, author of *Minnesota’s Geologist*, who entertained questions about Winchell’s life more broadly.

Feedback concerning the virtual meeting was overwhelmingly positive from those in attendance. Given the circumstances, the meeting proved to be very successful in providing an opportunity for researchers to present and discuss their work and for ILSG members to reconnect, albeit virtually. It is hoped that we will once again be able to meet in-person and partake in field trips once again in Sudbury in 2022.

Pete Hollings, Mark Smyk, and Mark Jirsa  
Co-Chairs, 67<sup>th</sup> Institute on Lake Superior Geology

# TECHNICAL PROGRAM

## **SATURDAY MAY 7, 2022**

All field trips begin and end at Science North

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

**5) A cross-section through the Huronian Supergroup at Elliot Lake, Ontario**

**Michael Easton** – Ontario Geological Survey

## **SUNDAY MAY 8, 2022**

All field trips begin and end at Science North

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

**1) A Traverse Across the Sudbury Impact Structure, Day 1**

**Wouter Bleeker** – Geological Survey of Canada

**Sandra Kamo** – University of Toronto

**Michael Leshner** – Laurentian University

**Henning Seibel** – Laurentian University

**2) Geology of the Grenville Front in the Sudbury area**

**Michael Easton** – Ontario Geological Survey

## **MONDAY MAY 9, 2022**

All field trips begin and end at Science North

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

**1) A Traverse Across the Sudbury Impact Structure, Day 2**

**Wouter Bleeker** – Geological Survey of Canada

**Sandra Kamo** – University of Toronto

**Michael Leshner** – Laurentian University

**Henning Seibel** – Laurentian University

4:00 pm - 10:00 pm **Registration** (Science North Atrium)

7:00 pm - 10:00 pm **Welcoming Reception and IMAX Movie** (Science North Atrium)

## **TUESDAY MAY 10, 2022**

8:00 am – 11:30 am **Registration** (Science North Cavern)

8:30      **OPENING REMARKS** (Science North Cavern)  
Michael Easton and Wouter Bleeker, Co-Chairs, 2022 ILSG

### **TECHNICAL SESSION I**

#### ***Session Chairs:***

**Mary Louise Hill** – Lakehead University

\* 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 abstract, if different than the first author.

8:40      **\*Ian Goan, Jackie Kleinsasser, Adam Simon, George Hudak and Dean Peterson**  
*Using the geochemistry of sulfides to understand the genesis of  
Ti-rich Fe-oxide ultramafic intrusions within the Duluth Complex, MN*

9:00      **Josh McQuade, Pete Hollings<sup>+</sup> and Matthew Brzozowski**  
*Sulfur isotopes as a record of differential contamination along the Cu-PGE mineralized  
Eastern Gabbro, Coldwell Complex, Canada*

9:20      **\*Rebecca Price, Roger Mitchell and Shannon Zurevinski**  
*Mineralogy and Petrology of the Good Hope Carbonatite Complex, Marathon, ON*

9:40      **Joyashish Thakurta and Kevin Rupp**  
*Episodic activation of magma conduits at the Midcontinent Rift System: Evidence  
from the Eagle system of intrusions in the Upper Peninsula of Michigan*

10:00      **COFFEE BREAK**

10:20      **David Kelly, Ted J. Bornhorst<sup>+</sup> and Chad Deering**  
*Fluid inclusions in euhedral calcite crystals from the Quincy Mine, Keweenaw  
Peninsula native copper district, Michigan*

10:40      **Timothy S. Hayes and Frank K. Mazdab**  
*Preliminary petrographic and geochemical data for potential source rocks for  
sediment-hosted stratabound copper deposits in the Lake Superior portion of the  
Midcontinent Rift*

11:00      **James DeGraff and Brad Carter**  
*Detached model of the Keweenaw fault system in western Lake Superior: Implications for  
its origin and relationship to rifting and orogenesis*

11:20      **Eben D. Hodgins, Nicholas L. Swanson-Hysell, Andrew Kylander-Clark, Andrew C.  
Turner, Daniel A. Stopler and Mark D. Schmitz**  
*Calibration of the timing and magnitude of a two-stage Grenvillian inversion of the  
Midcontinent Rift using U-Pb geochronology and clumped isotope thermometry on  
the Douglas Fault, WI*

11:40 **End of Technical Session I**

12:00 **LUNCH BREAK – BUFFET PROVIDED and LSG BOARD OF DIRECTORS MEETING**

## **TECHNICAL SESSION II**

### ***Session Chairs:***

**Michael Easton** – Ontario Geological Survey

1:30 **Robert Cundari, Pete Hollings<sup>+</sup> and Mark Smyk**

*The Evolution of Logan Igneous Suite; implications for mantle source heterogeneity and the development of the Midcontinent Rift System*

1:50 **Jim Miller, Steve Flank, Lionnel Djon, Jami Brown and Doug Nikkila**

*Lithostratigraphy, mineralization, and petrogenesis of the MCR-related Sunday Lake Intrusion, NW Ontario*

2:10 **Pete Hollings, Mark Smyk<sup>+</sup> and Mike Hamilton**

*Geology and Geochemistry of Midcontinent Rift System Rocks, Porphyry Island, Northern Lake Superior, Ontario*

2:30 **COFFEE BREAK**

2:50 **\*Alex Steiner, Dean Peterson and Gabriel Sweet**

*Magma Recharge and the distribution of copper and nickel in the Keweenaw Large Igneous Province*

3:10 **Matthew Deller and Ryan Weston**

*Geology and Emplacement of the Eagle's Nest Ni-Cu-PGE Deposit in the McFaulds Lake greenstone belt, Ring of Fire, northern Ontario, Canada*

3:30 **Dean Peterson and Ben Keute**

*Bringing the Wyoming Province and its orogenic gold potential home to the Superior Province, a look into the South Pass greenstone belt and its Abitibi gold links*

3:50 **Evan Hastie, Julian Melo-Gómez, Harold Gibson, Kim Tait and Joe Petrus**

*Gold Fingerprinting: Inspiration, project overview and method development*

4:10 **POSTER VIEWING - AUTHORS WILL BE PRESENT AT THEIR POSTERS**

4:30 **END OF TECHNICAL SESSION II**

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5:30 **RECEPTION AND CASH BAR** (Science North Cavern)

7:00 **ANNUAL BANQUET** (Science North Cavern)

- Announcement of 69<sup>th</sup> Annual Meeting Location
- **2022 Goldich Award Presentation to Terry Boerboom**

## **WEDNESDAY May 11, 2022**

8:40      **INTRODUCTORY REMARKS AND UPDATES** (Science North Cavern)  
Michael Easton and Wouter Bleeker, Co-Chairs, 2022 ILSG

## **TECHNICAL SESSION III**

### ***Session Chairs:***

**Michael Easton** – Ontario Geological Survey

**Wouter Bleeker** – Geological Survey of Canada

8:50      **Rajesh Vayavur, Richard Smith, Rasmus Haugaard, Ademola Adetunji, John Ayer, Mostafa Naghizadeh, Saeid Cheraghi, Ross Sherlock, Kevin Fenlon, Lisa Gibson and Warren Hughes**  
*3-D upper crustal architecture of the East range of the Sudbury basin – a Metal Earth collaborative research project with Vale & Glencore*

9:20      **Wouter Bleeker and Sandra Kamo**  
*The Sudbury structure, Earth's largest (partially) preserved impact crater—A review*

9:50      **Mark Smyk and Jim Miller**  
*Pioneer of Lake Superior Geology – Thomas L. Tanton*

10:10      **COFFEE BREAK**

10:30      **\*Audray M. Hinkemeyer, Howard D. Mooers and Philip C. Larson**  
*Characterizing Late Wisconsinan Rainy Lobe Till from the Hudson Bay Lowlands to SW Minnesota: Insights on provenance and ice sheet behavior during Late Wisconsin glaciation*

10:50      **Discussion**

11:00      **POSTER VIEWING - AUTHORS WILL BE PRESENT AT THEIR POSTERS**

12:00      **End of Technical Session III**

12:00      **LUNCH BREAK – BUFFET PROVIDED**

## **TECHNICAL SESSION IV**

### ***Session Chairs:***

**Michael Easton** – Ontario Geological Survey

1:20    **\*Miles Harbury, Julie Bowles, John Isbell**

*Determining the genetic origins of Paleoproterozoic diamictites using  
Anisotropy of Magnetic Susceptibility (AMS)*

1:40    **Caroline Gordon**

*Geology and geochemistry of the Elsie Mountain and Stobie Formations, Huronian  
Supergroup: Developing a chemostratigraphy to address challenges with the current  
subdivision*

2:00    **Discussion, Announcements, Impromptu Presentations**

2:20    **COFFEE BREAK**

2:40    **Impromptu Presentations**

3:15    **BEST STUDENT PAPER AWARDS  
STUDENT TRAVEL AWARDS  
CLOSING REMARKS**

3:30    **END OF TECHNICAL SESSIONS**

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## **THURSDAY MAY 12, 2022**

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

Field trips 3 and 4 begin and end at Science North

### **3) Magmatism and Brecciation in the Footwall Rocks of the southwestern Sudbury Structure**

**Caroline Gordon** – Ontario Geological Survey

**Carol-Anne G  n  reux** – Laurentian University, Terrane Geoscience

**Brad Clarke** – SPC Nickel Corporation

### **4) An overview of the geology of the Sudbury Structure**

**Shirley P  loquin** – Ontario Geological Survey

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## POSTER PRESENTATIONS

**\*Zsuzsanna P. Allerton, Tatiana Vislova, Terry Boerboom and Mark Jirsa**

*Ejecta deposits from the 1.85 Ga Sudbury meteorite impact in  
Crow Wing County, Minnesota*

**\*Connor Caglioti, Matthew Brzozowski, Pete Hollings and Geoff Heggie**

*Petrography and geochemistry of the Escape PGE–Ni–Cu sulfide deposit,  
Thunder Bay North Igneous Complex, northwestern Ontario, Canada*

**James M. DeGraff, Chad Deering and Aleksey Smirnov**

*Geological reconnaissance at Stannard Rock in eastern Lake Superior*

**\*Tianna Groeneveld, Pete Hollings, Wyatt Bain and Lionnel Djon**

*Geochemistry and mineralization of the Archean Titan (Roaring River) Intrusion,  
northwestern Ontario*

**Aidan Krieger, David H. Malone, John Craddock, Steven D.J. Baumann<sup>+</sup>, Shawn J. Malone  
and Daniel Holm**

*Continental-scale sediment dispersal of the Mesoproterozoic Baraboo Interval quartzites in  
the southern Lake Superior Region, USA*

**\*Katherine Langfield, James M. DeGraff, Nolan Gamet, Ian Gannon**

*Slip Kinematics of the Hancock Fault in the Midcontinent Rift System,  
Keweenaw Peninsula, Michigan*

**Timothy Nesheim, Bernhardt Saini-Eidukat and Jeffrey D. Vervoort**

*U–Pb zircon ages and Lu–Hf isotopes from Precambrian basement along the Trans-Hudson  
Foldbelt/Superior Craton Boundary Zone, central North Dakota*

**\*Khalid Yahia, Pete Hollings, Matthew Brzozowski, Allan MacTavish, Geoff Heggie  
and Abraham Drost**

*Geochemical and isotopic composition of Midcontinent Rift-related intrusions of the Thunder  
Bay North Igneous Complex, northwestern Ontario, Canada*

\* 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.

# ***ABSTRACTS***

## **Banquet Presentation**

### **Geoscience Site Characterization of the Revell batholith in the Ignace area**

**Andy PARMENTER**

*Nuclear Waste Management Organization, Toronto, Ontario*

The Nuclear Waste Management Organization (NWMO) is responsible for the long-term management of Canada's used nuclear fuel. NWMO launched a site selection process in 2010 to identify an informed and willing host community. From the initial 22 communities that expressed interest in learning more about the plan, on-going site characterization activities are now focused on two areas – first, the Ignace area, in northwestern Ontario, is located in Archean crystalline rock in the Canadian Shield; with the second, the South Bruce area, in southern Ontario, located in the Paleozoic sedimentary sequence of the Michigan Basin. The NWMO is currently conducting a variety of geoscience activities in these two areas, including the drilling and testing of deep boreholes, which allow for the collection of a unique set of geoscientific data from surface down to about 1 km below ground surface. This presentation will summarize the current status of geoscience site understanding of the Archean Revell batholith near Ignace.

### **Background Information**

Parmenter, A., Waffle, L. and DesRoches, A. 2020. Bedrock geology of the Revell batholith and surrounding greenstone belts; Nuclear Waste Management Organization, Technical Report NWMO-TR-2020-08, 61p.

## **Ejecta Deposita from the 1.85 Ga Sudbury Meteorite Impact in Crow Wing County, Minnesota**

**ALLERTON, P. Zsuzsanna<sup>1</sup>, VISLOVA, Tatiana<sup>1</sup>, BOERBOOM, Terrence<sup>2</sup>, and JIRSA, Mark<sup>2</sup>**

*<sup>1</sup>University of St. Thomas, Saint Paul, Minnesota, <sup>2</sup>Minnesota Geological Survey*

The purpose of this study was to investigate the extent of the 1.85 Ga Sudbury meteorite impact in the westernmost part of the Lake Superior area, Minnesota (MN), and look for rocks bearing evidence of ejecta deposits in two different locations — northern and southern parts of Crow Wing County, MN. The meteorite impact induced deformation may have resulted in spherules with shocked quartz, which are the best indicators of extra-terrestrial forces. However, the farther the ejecta traveled from the origin of the impact site, the less likely deposits would contain shocked quartz, but they could leave behind characteristic features in the country rock.

New attributes were discovered and described during a comprehensive analysis of thin sections made from core samples, with features conceivably related to ejecta deposition. The thin sections from the northern drill core encompass spherules in a disturbed or chaotic matrix (Figure 1). Similar spherulitic characteristics were found in other ejecta bearing locations. Research by Cannon et al. (2010) on Sudbury ejecta in Michigan reported indistinguishable spherulitic features; with similar size and rim structure, but different mineralogy and shape. Their description of the spherule is “Accretionary lapilli flattened along the bedding” (Cannon et al, 2010), but our spherules have a more rounded shape without flattened edges and appear to contain more opaque minerals and fewer quartz grains. Our samples contain devitrified glass fragments that are described as “altered melt droplets” (Huber et al., 2014) in other studies related to the Sudbury impact (Figure 2). Devitrified glass can be an indicator of meteorite impacted rocks.

Thin sections from the southern drill core revealed remarkable and varied features. One thin section includes melt droplets with chaotic appearance (Figure 3) that are similar to terrestrial deposits due to volcanism, therefore the sample requires further testing to conclude ejecta deposition. Accretional lapilli are present in the southern drill cores and are more similar in terms of shape to the ones reported by Canon at al. (2010). However, our lapilli are either made of chert or chlorite. The random shape and distribution of the lapilli requires further investigation, beyond the scope of this study. Lapilli are concentric and layered features and can form as a result of volcanism or meteorite impact (Jirsa et al., 2011). Volcanism is neither proven, nor ruled out at this locality. The general chaos manifested in the drill core samples can be attributed to ejecta deposition. One thin section includes a 10-mm long piece of chert located randomly and abruptly in the matrix of the sample (Figure 4). The chert does not appear to be part of the original formation; thus, it must have been ejected then deposited in the layer, deforming the local rock bed. The dark mineral cluster could either be deformed local matrix or melt. The disorder displayed in the thin sections indicate disruptions that need further mineralogical and geochemical analysis to support a more comprehensive argument for ejecta depositional features being present in the samples. Although the thin sections contain quartz, evidence of shocked features is absent.

In conclusion, the study areas could have been subjected to ejecta deposits shortly after the Sudbury meteorite impact, based on features comparable to those of previously confirmed ejecta. The features found in the two core samples have potential deformation indicators of extraterrestrial forces. Continued research on these core samples and others in their vicinity, including geochemical analysis of trace elements, detailed mineralogy, and iridium testing, would be invaluable in determining the presence of ejecta deposits at these locations with greater certainty.

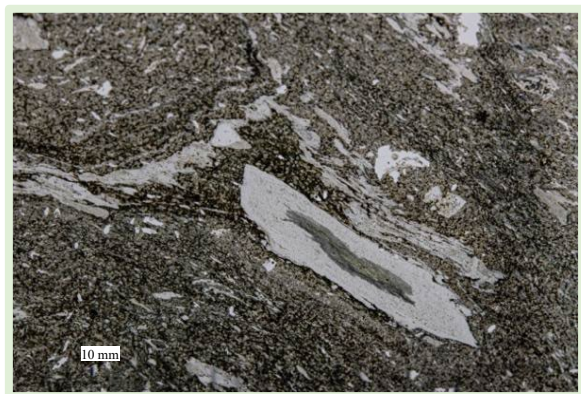


**Figure 1:** Chert lapilli in plane-polarized light.

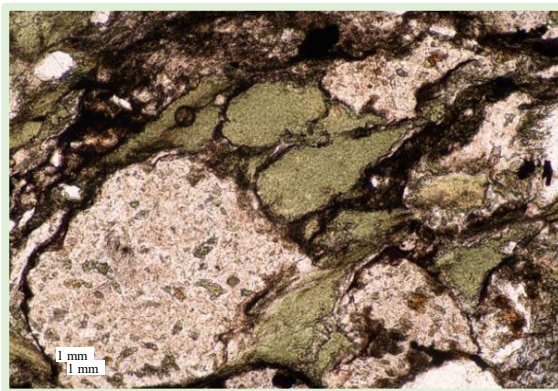


**Figure 2:** Dark areas in matrix resemble devitrified glass.

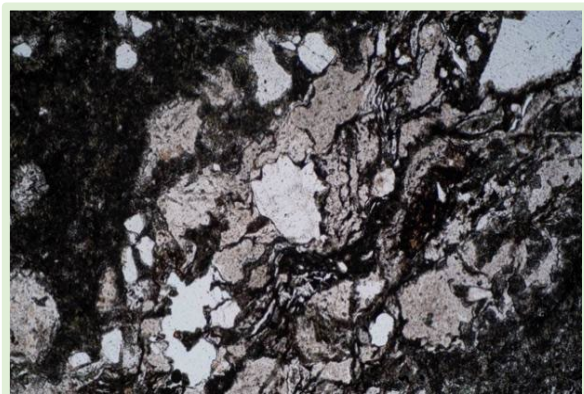


**Figure 3:** Plane-polarized light image shows melt droplets and disturbances in the rock.



**Figure 4:** Plane-polarized light image of “flying” chert with 10mm diameter.

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## The Sudbury structure, Earth's largest (partially) preserved impact crater—A review

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The Sudbury structure represents the somewhat incomplete and variably deformed remnants of a large, multi-ring meteorite impact crater precisely dated at 1850.0 Ma (Stöffler et al., 1989; Grieve et al., 1991; Pye et al. 1984, and contributions therein; Bleeker and Kamo, 2022). It is located in the southern Canadian Shield, in an area of moderately complex basement geology characterized by multiple tectono-metamorphic (magmatic) fronts. Some of these fronts pre-date, whereas others post-date, the precisely timed impact event (Figure 1).

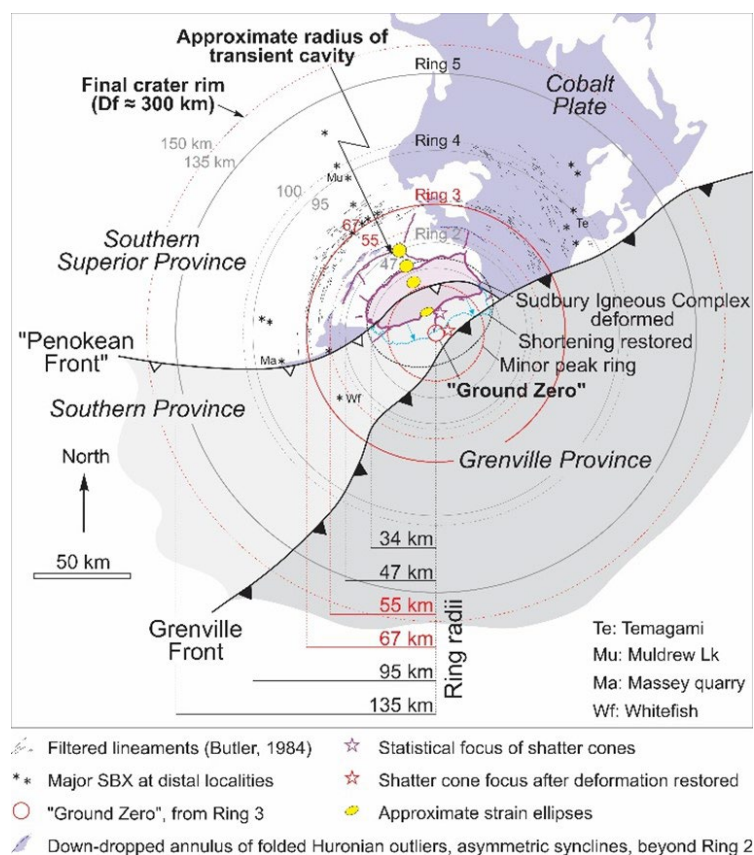


**Figure 1:** Summary map of the deformed Sudbury structure (SIC outline and related “offset” dykes in purple), on or near the boundary of several structural provinces: the Archean southern Superior Province, the Paleoproterozoic Southern Province, and the Mesoproterozoic Grenville Province. Ring structures in the relatively undeformed foreland (Butler, 1994; particularly Ring 3, in red; see also Spray et al., 2004), allow definition of “Ground Zero”. The deformed and preserved SIC largely overlies the northern part of the broad, collapsed, central uplift area with a diameter of ~80–90 km. This is surrounded by a down-folded and down-faulted annulus defined by asymmetric synclinal outliers of Huronian cover rocks, with a diameter of ~100–110 km. Scaling parameters (e.g., see Theriault et al., 1997) suggest a final crater diameter of ~300 km (see Bleeker and Kamo, 2022, and more complete discussion and references therein).

Although some of the igneous rocks associated with the structure, generally referred to as the Sudbury Igneous Complex or SIC (Pye et al., 1984), were long known to geologists, it took the better part of a century for the realization to emerge that they are fundamentally linked to a large meteorite impact; and another 20–30 years for this realization to become widely accepted. Watershed or paradigm-shifting events in this process were: 1) The recognition by Robert Dietz, in the mid- to late-1950s, that “shatter cones” represent key structural indicators, at the outcrop scale, for very high-energy impact shock waves (Dietz, 1959). 2) His visit to the enigmatic Sudbury structure in 1962, during which he quickly recognized shatter cones all through the brecciated footwall rocks, and, consequently, posited an impact origin (Dietz, 1964)—albeit still a hybrid origin to some degree. 3) The emergence of various whole-rock isotopic data (e.g., Faggart et al., 1985), that showed that all of the SIC igneous rocks, even the more mafic ones, were characterized by values that suggested wholesale melting of the local crust, with little or no mantle input.

These developments finally resulted in the general acceptance of what is essentially an “impact only” interpretation of the structure and its igneous rocks, with the latter recognized as the remnants of a thick and aerially extensive, differentiated, impact melt sheet (Stöffler et al., 1989; Grieve et al., 1991). The melt sheet, now deformed and largely eroded, is underlain by an extensively brecciated footwall, and overlain by ~2 km of upward-fining suevitic breccias that represent, in a broad sense, the ejecta that fell back or were washed back into the crater. The collapsed and rebounded crater, overlain by the settled melt sheet and fall-back breccias, and post-impact sediments, was then deformed by the Penokean and subsequent regional deformation events, between ca. 1840 and 1650 Ma, largely in a north-northwesterly direction. Deformational effects of the Grenville Front, which occurs a mere ~10–15 km to the southeast of Sudbury, and essentially truncates the pre-1.1 Ga geology, are relatively minor within the preserved Sudbury structure itself, perhaps mostly contributing to regional tilting and uplift in the foreland.

The northwestern part of the deformed impact structure, albeit relatively deeply eroded, is least deformed. Relatively well-defined patterns of shock features and collapse-related lineaments allow recognition of impact-related ring structures (Butler, 1984), which, as they are pinned to the relatively undeformed foreland, allow the centre of impact (“Ground Zero”) to be defined with some precision. This best estimate for “Ground Zero” agrees with a statistical focal point of best-preserved shatter cones in the footwall, with the latter located along the central part of the South Range of the SIC, but after restoring the shortening deformation overlaps with Butler’s “Ground Zero”. From this we estimated that the differentiated melt sheet, with an average thickness of ~2–3 km, reached out to a radius of ~67–70 km and had an original volume of ~20–50 x10<sup>3</sup> km<sup>3</sup>. Only ~10% of this melt volume is represented by the present erosional remnant of the SIC. All of the preserved but folded melt sheet (the SIC) represents a relatively proximal part of the northern half of the original melt sheet (e.g., see Figure 1). Hence, there is little a priori reason for symmetry between the preserved North Range and South Range of the SIC (Bleeker and Kamo, 2022).

The preserved melt sheet largely overlies the remnants of a broad, collapsed, central uplift reaching outwards to a maximum radius of ~45 km. As in all multi-ring impact structures, this collapsed central uplift is surrounded by the relatively well-defined remnants of a deeply down-folded and down-faulted annulus, here characterized by tight asymmetric synclinal outliers of pre-impact Huronian cover rocks, with fold axes that define a >90° arc around the northern half of the structure. The radius of this annulus is ~55 km (i.e.  $D_a \approx 100\text{--}110$  km). The diameter of this annulus is larger than the well-defined annulus (~90 km) of the deeply eroded Vredefort structure in South Africa, suggesting Sudbury is the largest preserved (and recognized as such) impact structure on Earth, with a final crater diameter approaching ~300 km.

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## Petrography and geochemistry of the Escape PGE–Ni–Cu sulfide deposit, Thunder Bay North Igneous Complex, Northwestern Ontario, Canada

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The 1.1 Ga Midcontinent Rift System (MRS) preserves abundant extrusive and intrusive magmatism formed during the failed attempt to break apart the North American craton. MRS rocks are located around the Lake Superior region, with several mafic–ultramafic intrusions host to orthomagmatic Ni–Cu–platinum-group element (PGE) mineralization (Woodruff et al., 2020). The Thunder Bay North Igneous Complex (TBNIC) comprises a series of MRS-related mafic–ultramafic intrusions that were emplaced into the Archean Quetico Basin of the Superior Province. The Escape deposit of the TBNIC comprises variably altered wehrlites that host PGE-rich orthomagmatic sulfide mineralization. Mineralization chiefly occurs as disseminated to net-textured sulfides, with lesser amounts occurring as blebs and veinlets. The sulfide assemblage typically comprises pyrrhotite, chalcopyrite, and pentlandite, with lesser to trace cubanite, pyrite, and millerite (Fig. 1A, 1B).

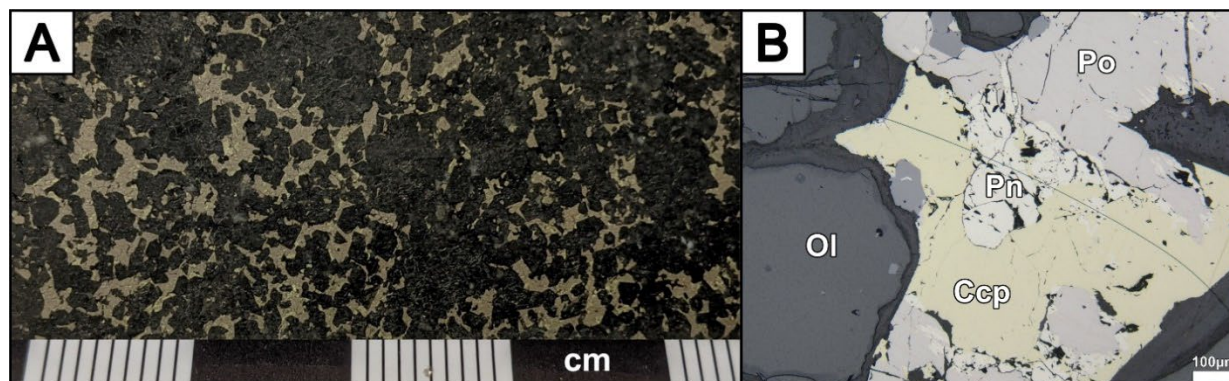


Figure 1: Images of net-textured sulfide mineralization from diamond drillhole ELR20-002. A. Photograph of sample CAM-21-CC-116. B. Reflected, plane polarized light photomicrograph of the same sample depicting pyrrhotite, chalcopyrite, and granular pentlandite interstitial to silicate phases.

This study will investigate the critical ore-forming processes of the Escape system, particularly the mechanisms that caused sulfur saturation and that contributed to the enrichment of metals in the sulfide minerals. Mechanisms that may have contributed to ore-formation include contamination of the silicate melt by externally derived S and interaction of the sulfide liquid with large volumes of silicate magma (i.e., R factor; Campbell and Naldrett, 1979). The extended primitive mantle-normalized trace-element patterns for the ultramafic rocks at Escape (Fig. 2) are similar to ocean island basalts and other MRS-related ultramafic intrusions (e.g., Disraeli, Kitto), indicative of a mantle plume source. The lack of Th enrichment and negative Nb anomaly suggest that the Escape magma(s) did not assimilate significant Archean Quetico metasedimentary rock, which are characterized by high Th/Nb ratios.

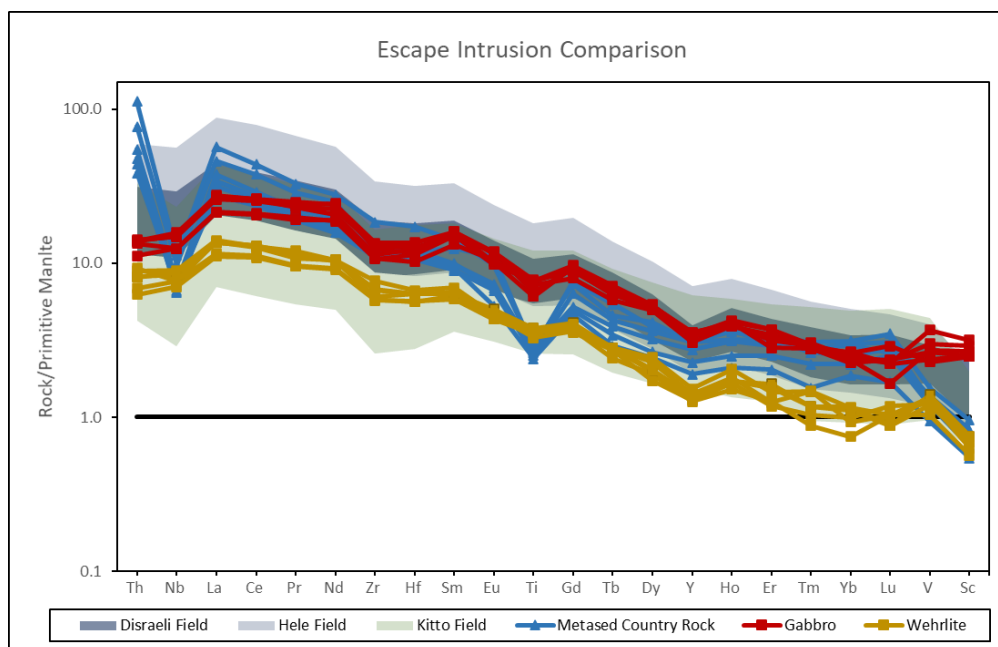


**Figure 2:** Spider diagram depicting a gently sloping negative trend for Escape rocks that are similar to ocean island basalts (OIBs). Whole-rock data from Escape is plotted with fields from other mafic-ultramafic MRS-related intrusions and Quetico schists.

This does not necessarily rule out the possibility that S was added to the system from an external source (e.g., the metasedimentary and granitic country rocks) via selective contamination. This possibility will be evaluated further using multiple S isotopes, as  $\Delta^{33}\text{S}$  may exhibit a mass-independent fractionation signal. This will help to assess the importance of different sulfur reservoirs in the formation of an immiscible sulfide liquid within the Escape chonolith and, ultimately, to the formation of PGE-rich sulfides.

To characterize metal deportment among the sulfides, detailed mineral chemistry will be obtained via SEM-EDS and LA-ICP-MS; these data will also permit assessment of the role of S addition and R factor in generating the mineralization at Escape. Variations in R factor can also be evaluated in bulk-rock Cu/Pd-Pd space, where high-R factor, PGE-rich systems plot at lower-than-mantle Cu/Pd values and high Pd values. On this diagram, the trend for the Escape deposit falls within the range of mantle values and is relatively flat (i.e., limited variation in Cu/Pd and large variation in Pd), indicating less system complexity (i.e., less variability in R factor) relative to other world-class magmatic Ni-Cu-PGE deposits (e.g., Norilsk-Talnakh, Marathon, and Jinchuan). The ultimate goal of the project is to integrate these diverse data to develop a holistic genetic model of the Escape deposit that will lead to improved exploration criteria.

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## The Evolution of Logan Igneous Suite; implications for mantle source heterogeneity and the development of the Midcontinent Rift System

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The 1.1 Ga Midcontinent Rift System (MRS) of North America comprises a series of Mesoproterozoic flood basalts and intrusive rocks emplaced in the Lake Superior region. Mafic intrusive rocks preserved on the northern, Canadian flank of Lake Superior represent the older portions of the rift sequence and belong to the Logan Igneous Suite, part of the Midcontinent Rift Intrusive Supersuite (cf. Miller et al., 2002). Here we present an update to Cundari et al. (2013) refining our understanding of the geochemical evolution of the intrusive rocks of the Logan Igneous suite in Ontario and offer insights into the early development of the rift. Reevaluation of a large whole-rock geochemical dataset from intrusive rocks south of Thunder Bay in the Logan Basin and in the Nipigon Embayment has revealed many previously unrecognized relationships between the intrusive units of the Logan Igneous Suite.

Evaluation of plots of Nb/Yb<sub>pm</sub> versus Gd/Yb<sub>pm</sub> (Fig. 1), Nb/Yb<sub>pm</sub> versus Th/Yb<sub>pm</sub> (Fig. 2) and Th/Yb<sub>pm</sub> versus Nb/Th<sub>pm</sub> (Fig. 3) within the context of an emplacement sequence derived from paleomagnetic and geochronologic data suggests a model for the progression of Logan Igneous Suite magmatism from a more enriched mantle source to a more depleted mantle source through time (cf. Bleeker et al., 2020). The data presented here show that five geochemically distinct mantle source regions were likely sourced to form the rocks of the Logan Igneous Suite, each with its own distinct contamination history and perhaps different degrees of partial melting. Additionally, improved constraints on the geochronology contributes to an evaluation of the geochemical evolution of MRS-related intrusive rocks in Ontario. The geochemical variations observed in Figures 1, 2 and 3 may suggest either a progressive depletion in the mantle source over time or heterogeneity of the source region. The interpretations presented here suggest a complicated magma plumbing system responsible for magma production early in MRS history. The presence of distinct mantle source regions early in the rift history, in addition to several distinct mantle sources throughout a protracted magmatic history, support a complex, heterogeneous mantle source feeding MRS magmatism. The geochemical interpretations presented here, in conjunction with emerging evidence for rapid plate motion during MRS (Swanson Hysell et al., 2019) as well as absence of a radial dyke swarm and lack of regional tilting or crustal doming in the MRS, suggest that traditional models invoking a single ascending mantle plume may need to be re-evaluated and a passive rift model for the MRS might be more appropriate.

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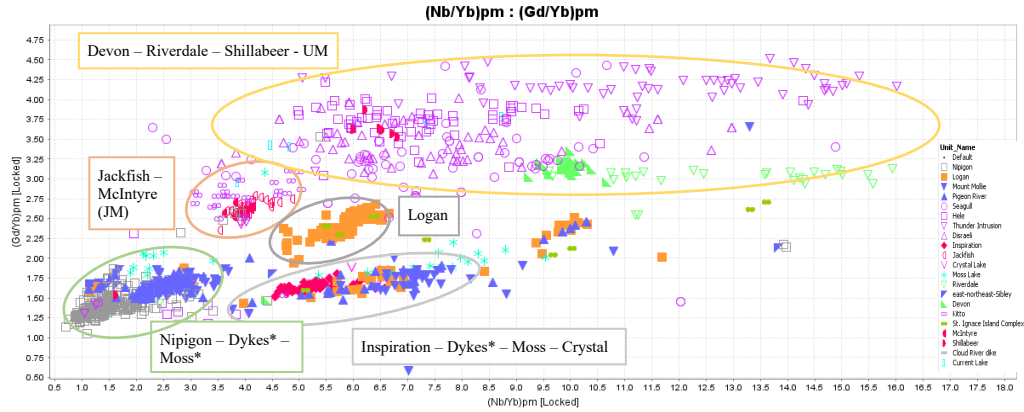


**Figure 1:** Plot of  $Nb/Yb_{pm}$  vs.  $Gd/Yb_{pm}$  ratios for Logan Igneous Suite rocks. Normalizing values from Sun and McDonough (1989). Data from Cundari et al. (2021b).

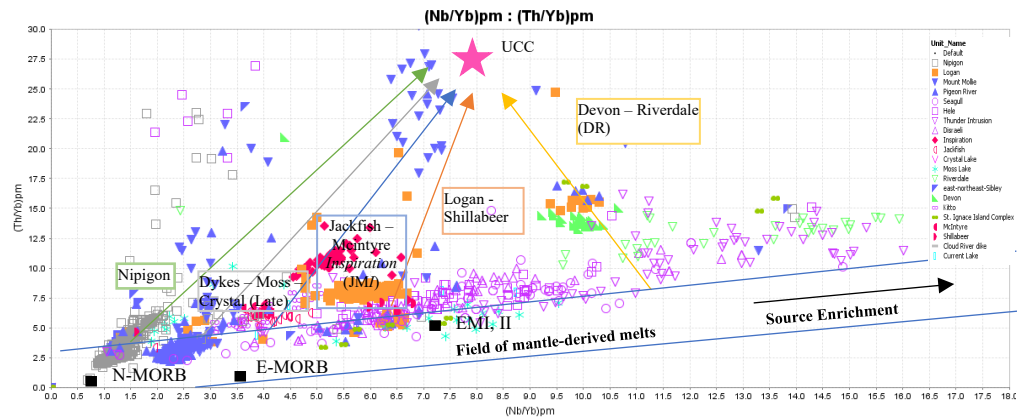


**Figure 2:** Plot of  $Nb/Yb_{pm}$  v.  $Th/Yb_{pm}$  ratios for Logan Igneous Suite. Normalizing values from Sun and McDonough (1989). NMORB and EMORB composition from Sun and McDonough (1989), enriched mantle values (EM1, II) from Condie (2001) and average Upper Continental Crust (UCC) composition is from Taylor and McLennan (1985). Data from Cundari et al. (2021b).

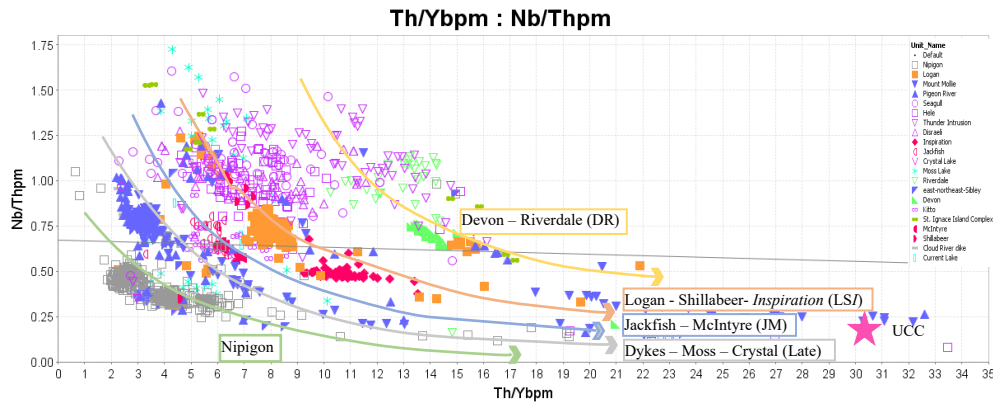


**Figure 3:** Plot of  $Th/Yb_{pm}$  vs.  $Nb/Th_{pm}$  ratios for Logan Igneous Suite rocks. Normalizing values from Sun and McDonough (1989). Average Upper Continental Crust (UCC) composition is from Taylor and McLennan (1985). Data from Cundari et al. (2021b).

For a more comprehensive discussion of the results and interpretation presented here, reference should be made to Cundari et al. (2021a).

## Detached model of the Keweenaw fault system in western Lake Superior: Implications for its origin and relationship to rifting and orogenesis

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The Keweenaw fault is perhaps the most significant fault in the Lake Superior region based on its trace length of 250 km and inferred 9 km of slip (1) that thrust copper-bearing Portage Lake Volcanics (PLV, ~1.1 Ga) over Jacobsville Sandstone (JS, ~1.0 Ga) (Fig. 1). This major fault along the southeast flank of the SW-trending branch of the Midcontinent Rift System (MRS) has figured prominently in ideas about MRS development (2-3) and copper deposits mined along the Keweenaw Peninsula (4). Bedrock geology maps show the fault trace being parallel to strike of hanging-wall PLV strata, which are juxtaposed against JS strata nearly everywhere. Published cross-sections generally show hanging-wall strata as subparallel to the fault and having a simple listric geometry, whereas footwall JS strata are tilted steeply southeast near the fault.

Ideas about the origin of the Keweenaw fault largely date to before modern concepts about thrust faults and before advances in cross-section modeling. A widely held view (1-2) is that the fault formed as a normal fault during MRS extension and later converted to a reverse fault during orogenic compression. A recent model (3) suggests that the fault was not a major normal fault during MRS extension but perhaps was present as such. Such scenarios favor a fault dipping  $> 45^\circ$  NW, however trenching and published cross-sections show the Keweenaw fault dipping  $\leq 45^\circ$  NW for much of its length (5, USGS 1950s maps). PLV layers have slipped along many boundaries (4, 6) and are subparallel the fault's surface. These observations suggest a fault system detached along PLV layers, which is inconsistent with inheritance from a rift-related normal fault.

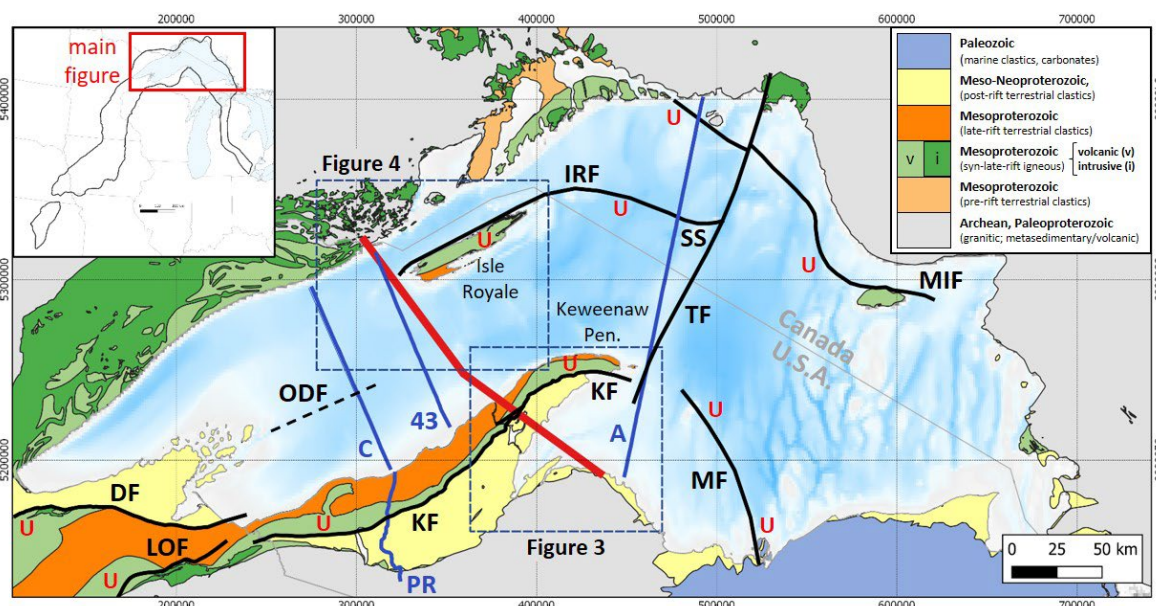


**Figure 1:** Mesoproterozoic units of the Midcontinent Rift System mostly from USA-Canadian government sources. Major faults: KF–Keweenaw, DF–Douglas, ODF–offshore Douglas, IRF–Isle Royale, MIF–Michipicoten Island, TF–Thiel, MF–Munising (provisional). Bold red line marks line of cross-section.

To evaluate existing ideas about the Keweenaw fault, we used current concepts and methods to construct a cross-section from the Keweenaw Peninsula to older bedrock on both sides of the MRS (Fig. 2). Constraining data for the cross-section include onshore geologic maps and core logs, an offshore seismic line, seismic refraction profiles, and gravity data. We consider the cross-sectional geometry to be well constrained on the Keweenaw Peninsula to about 5 km depth and relatively well constrained offshore to about 15 km depth. Uncertainties in reconstructing cross-sectional geometry arise from material having been removed by erosion along the spine of the peninsula, relatively poor knowledge of units preserved in the footwall, and no direct information about the nature of seismic units under the lake.

We interpret the Keweenaw fault and the nearby Hancock fault as being connected above 4 km depth, with the lesser Hancock fault having about 750 m of reverse slip. Above this connection, the Keweenaw fault cuts to the surface with a dip as low as 20° based on drill hole data and possibly as low as 10° based on modeling. Below the connection, we model the Keweenaw fault with a listric geometry to explain the geometry of hanging-wall strata whose dip systematically decreases from 55° NW at the spine of the peninsula to < 20° NW at the shoreline. Geometric relationships suggest that the fault becomes parallel to strata deep within the PLV section and perhaps at its base, implying that it was not derived from a rift-related normal fault. Stratal geometry between the Keweenaw and Hancock faults at surface allows reconstruction of a virtual anticline with 3-4 km of material removed. Based on the anticline's geometry and seismic estimates of footwall sediment thickness, we infer between 7.5 km and 10.5 km of reverse slip on the Keweenaw fault. Our cross-section model and recent dates that constrain timing of Keweenaw fault movement indicate that the fault initiated as a detached thrust during a phase of the Grenville Orogeny.

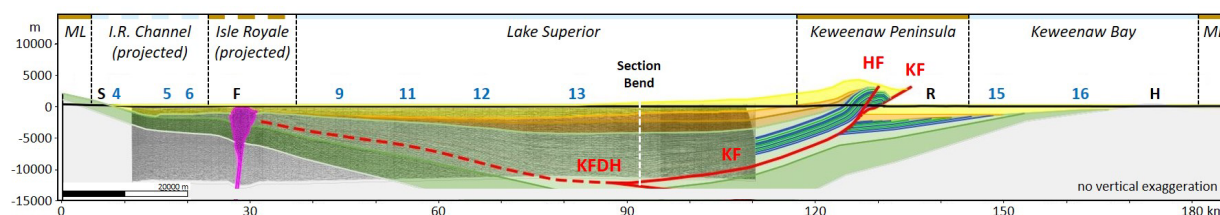


**Figure 2:** Regional structure section across the southwestern branch of the Midcontinent Rift System.

**Acknowledgements:** We have benefitted greatly from discussions with V.J.S. Grauch and L.G. Woodruff (USGS), T.J. Bornhorst (MTU), E.B. Hodgins and N.L. Swanson-Hysell (UC-Berkeley).

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## Geological reconnaissance at Stannard Rock in eastern Lake Superior

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Stannard Rock was first noted as a marine hazard in 1835 by Charles T. Stannard, captain of the schooner John Jacob Astor that sank at Copper Harbor (MI) in 1844. In 1868 a beacon atop iron posts was erected on the small rock (Fig. 1), only 10 m across in calm seas, but it was quickly destroyed by winter ice. During construction of a lighthouse between 1878 and 1883, a rock sample was provided by a Mr. J. Chassells to USGS geologist R.D. Irving who described it as an “aphanitic, dark reddish-brown...felsite” with 66% SiO<sub>2</sub> (1). Since Irving’s USGS monograph, no other geological data from Stannard Rock has been published.

Though merely a small wave-swept islet, Stannard Rock is the barely emergent crest of a large, underwater, bedrock plateau that extends nearly 13 km NE-SW by 5 km wide (2) and rises abruptly from surrounding depths of 180 m to less than 10 m over its top (Fig. 1). This area in eastern Lake Superior lies along the SE-trending branch of the Midcontinent Rift System (MRS), whose bedrock is less exposed and less well investigated than MRS bedrock along the SW-trending branch. Bedrock exposed at Stannard Rock and presumed underwater exposures across the much larger plateau allow sampling of rocks on the west flank of the SE-trending MRS branch that are not accessible elsewhere, except in core from the Amoco St. Amour 1-29R well southeast of Munising (MI). We collected samples from the islet south of the lighthouse and are analyzing them to obtain new data and understanding about rocks along the SE-trending MRS branch.

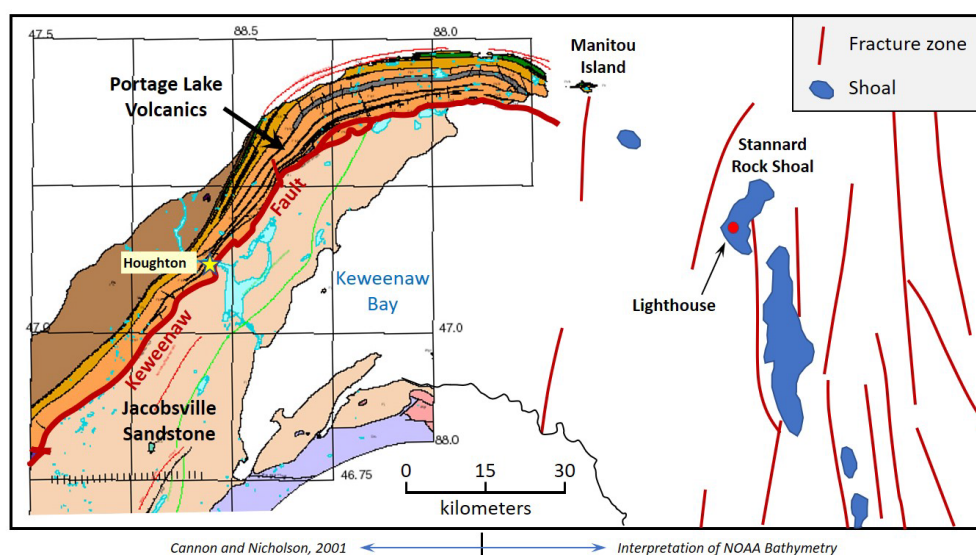


**Figure 1:** Geologic setting of Stannard Rock shoal, located 45 km southeast of Keweenaw Point. Onshore geology is from (4) and offshore fracture zones are interpreted from (5).

Results to date are consistent with Irving’s description of the one specimen he examined, and we now have more information about the nature of the rock at the islet. Macroscopically, the islet consists of a very hard, medium to dark reddish-brown, aphanitic rock that displays rough flat surfaces dipping less than 15° SSE. The flat outcrop surfaces are fractures subparallel to cm-scale layering defined by subtle variations in color and texture. Microscopically, the layers vary irregularly in thickness and have transitional boundaries with adjacent layers. Cavities with long

dimensions parallel to layering occur within lighter layers and are filled by isolated quartz, surrounded by a medium brown mineral with a radial habit (zeolite?) and an opaque mineral. The very fine-grained groundmass consists mostly of unaligned, acicular, pinkish and greenish white minerals that surround opaque to dark brown, irregular, tabular minerals. Variation in abundance of these minerals accounts for the observed layering, with the ratio of light acicular to dark tabular minerals being about 80:20 in lighter layers and 60:40 in darker layers. Geochemical classification of three samples indicates that they are trachyte, based on the TAS system (3), with 64-65% SiO<sub>2</sub> and 9-10% Na<sub>2</sub>O+K<sub>2</sub>O after recalculation for LOI ( $\leq 2.0$  %). Based on these preliminary observations, we identify the sampled rocks at Stannard Rock as flow-banded trachyte, consistent with Irving's original description.

The area around the lighthouse has two local shoals with layering that dips shallowly northeast and southeast based on analysis of aerial and satellite images, and by analogy with direct observations at Stannard Rock (Fig. 2). The shoal east of the lighthouse has a long dimension of 450 m trending 300° and has shallow dips toward 30° azimuth. The shoal southeast of the lighthouse has a long dimension of 800 m trending 10° and has shallow dips toward 100° azimuth. These inferred dip azimuths together with measured SSE dip at Stannard Rock at the south end of the area define a roughly arcuate structure that may result from deformation or may represent original dip. Paleomagnetic work on samples oriented by sun compass yield a reverse magnetic polarity, which may indicate that these rocks are part of the older volcanic series in the region if the signal is free of secondary effects, say, due to lightning. We plan to expand the work by collecting additional samples from the two local shoals near the lighthouse and by obtaining low-altitude imagery using UAV imaging and photogrammetry.

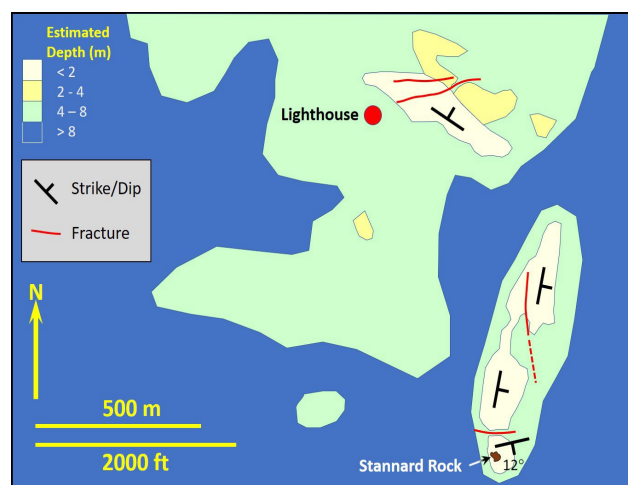


**Figure 2:** Structural configuration of Stannard Rock shoal near the lighthouse; based on measurements at the islet and interpretation of aerial and satellite imagery.

**Acknowledgements:** This skunk work has been cobbled together with financial and logistical assistance from the Great Lakes Research Center (Michigan Tech) and with a research gift from Bruce Marsh (Johns Hopkins). We also thank Sophie Mueller, Daniel Trekas, and Capt. Travis White for assistance collecting samples; and Gabe Ahrendt for paleomagnetic lab work.

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## **Geology and Emplacement of the Eagle's Nest Ni-Cu-PGE Deposit in the McFaulds Lake Greenstone Belt, Ring of Fire, Northern Ontario, Canada**

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The Esker intrusive complex (EIC) is part of a series of mafic-ultramafic intrusions, including the Black Thor, Double Eagle and Eagle's Nest intrusions, of the 2734 Ma Koper Lake sub-suite within the larger Ring of Fire intrusive suite within the McFaulds Lake greenstone belt in the Ring of Fire region (Metsaranta & Houlé, 2020; Houlé et al., 2020). It is host to both magmatic Ni-Cu-(PGE) and chromite mineralization. Located in the James Bay Lowlands of Northern Ontario, the RoF region has been the focus of mineral exploration since the early 2000s culminating in the delineation of the Eagle's Nest Ni-Cu-(PGE) magmatic sulfide deposit, and a series of high-grade and large tonnage chromite deposits (e.g., Black Thor, Blackbird).

The EIC was emplaced near the stratigraphic base of the McFaulds Lake greenstone belt, at the contact between a 2773 Ma footwall tonalite-granodiorite and hangingwall supracrustal rocks of the ca. 2780 Ma Victory Assemblage or younger 2734 Ma Muketei Assemblage. While not yet dated, the DEI is believed to be coeval with the 2734 Ma Black Thor intrusion, located 7km to the northeast.

The Double Eagle Intrusion (DEI), which forms part of the EIC and is host to the BB2-1 massive chromite lens, is cut by Frank's Shear Zone (also referred to as the Triple-J fault) resulting in division of the DEI into the AT1 segment to the north, and the Blackbird segment to the south. When re-constructed, the DEI has a transitional chonolith-sill form with a pointed dyke-like base defined by AT1, and a wider, crudely layered sill-like top defined by the Blackbird segment. The Eagle's Nest dyke occurs as an isolated intrusion 100-150m stratigraphically below AT1.

The Blackbird segment of the DEI is interpreted to young to the southeast based on an igneous fractionation trend of olivine-chromite dominant lithologies in the northwest and pyroxenite-gabbro-diorite dominant lithologies in the southeast. The BB2-1 chromite horizon, which occurs near the top of the ultramafic series at Blackbird, is interpreted to have been originally deposited as sub-horizontal layers, and has since been tilted through deformation to a sub-vertical to slightly overturned orientation. This interpretation is in agreement with the younging directions at the Black Thor intrusion as well (Metsaranta & Houlé, 2020).

The Eagle's Nest ultramafic intrusion is a bladed-dyke in form. Although no physical link has been identified with the DEI, it may have been a feeder conduit to the larger overlying intrusion (Houlé et al., 2020). In its present orientation the Eagle's Nest dyke is sub-vertically plunging, with a height of ~150m, a width of ~500m and a dip extent of >1600m. Given the geometry of the intrusion, internal fractionation trends, presence of magmatic breccias and the distribution of sulfides, it is interpreted to have been sub-horizontally emplaced with magma flow direction downwards in its current position. Modest but mappable changes in the plunge of the chonolith are interpreted to reflect changes in the path of ascending magma flow from inclined to sub-horizontal where the trend of the dyke becomes parallel to igneous layering in the overlying Blackbird segment. This interpretation is supported by the presence of magmatic breccias at these orientation changes, which are interpreted to reflect incipient damage zones along the path of magma ascent. The presence of massive sulfide in the inclined portion of the dyke is interpreted to reflect topographic embayments along its base. Sulfide accumulations here may have been further aided by back-flowing sulfide liquid towards the end of the active emplacement of the magma.

Development of the chonolith is hypothesized to have occurred as a progression of narrow dykes which, through sustained magma flow and consumption of host tonalite, broadened to form the Eagle's Nest dyke as suggested by Houlé et al. (2019, 2020) for the EIC in a manner similar to the mechanisms proposed by Barnes & Mungall (2018). It is during this sustained magma flow-through that sulfide saturation would have likely occurred within the chonolith followed by segregation and accumulation of sulfides to basal portions of the chonolith driven by density contrasts.

Mineralization at Eagle's Nest is found semi-continuously along the base of the bladed-dyke. The bulk of the mineralization present occurs as net textured to heavily disseminated sulfides (Zuccarelli et al., 2022) with massive sulfide most commonly occurring along the northwest margin of the intrusion where it is in sharp contact with overlying net textured sulfide. Silicate phases are dominated by olivine-pyroxene orthocumulates (lherzolite-peridotite), with no olivine adcumulates (dunite) observed. Sulfide bearing lithologies tend to be more primitive, while the upper portions of the dyke grade into unmineralized peridotite and pyroxenite. A significant proportion of orthopyroxene is present within the rocks. Chromite does occur, but only in cotectic proportions (~1%), no significant accumulations of chromite are identified within the Eagle's Nest chonolith, however, some cm-scale chromite clasts have been found locally (Zuccarelli et al., 2022).

Previous studies by Mungall et al. (2010) and Azar (2010) have estimated a low MgO komatiitic parental magma composition for the DEI of ~22% MgO and ~12% FeO<sup>t</sup>, in comparison to an estimated parental magma composition for the Black Thor intrusion of ~28% MgO and ~10% FeO<sup>t</sup> or high MgO komatiite (H.J.E. Carson, pers. commun., 2019). However, a recent review of 29 chilled margin samples along the Eagle's Nest dyke might suggest a less primitive parental magma composition of ~14% MgO, ~9% FeO<sup>t</sup>, ~700ppm Ni, and 800ppm Cr with elevated PGE values that could favor a picritic parental magma rather than a komatiitic parental magma. This is supported by olivine compositions at Eagle's Nest which range from Fo<sub>80-87.6</sub> with an average of Fo<sub>84</sub> obtained from 116 point analyses (Azar, 2010; Zuccarelli et al., 2022), however, we cannot rule out completely that the most magnesian olivine at Eagle's Nest has yet to be analyzed. Furthermore, a suite of aphanitic mafic dykes in the direct vicinity of the Eagle's Nest chonolith contain similar compositions and show an olivine control on Ni concentration. Further work is needed to confirm these observations, but a less primitive (i.e. picritic) parental magma for Eagle's Nest may better explain the high Cu-PGE budget relative to Archean komatiite systems elsewhere.

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## Using the geochemistry of sulfides to understand the genesis of Ti-rich Fe-oxide ultramafic intrusions within the Duluth Complex, MN

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The Duluth Complex formed 1.1 Ga as a part of the Midcontinent Rift System when a series of massive mafic intrusions were emplaced in northeastern Minnesota. The rock types within this complex include a series of gabbroic, troctolitic, and anorthositic intrusions which protruded into the Archean and Paleoproterozoic footwall. This footwall comprises the metasedimentary rocks of the Biwabik Iron Formation and the Virginia Formation, the latter containing a sulfur-rich, black shale layer known as the Bedded Pyrrhotite Unit.

The Duluth Complex host numerous mineral deposits, including Cu-Ni, PGE, and Ti, yet remains largely understudied and underdeveloped in terms of mineral potential. Significant Fe-Ti mineralization represents one of the United States' most promising domestic resources and is hosted within 12 Fe-Ti oxide-bearing ultramafic intrusions (OUIs) located along the western margin of the Duluth Complex near the Virginia Formation footwall. These OUIs were first identified in geophysical studies, but there have been no geochemical analyses done on them in the past.

We analyzed samples from two OUIs, Longnose and Titac, using thin sections made from available drill core. Utilizing reflected light microscopy, scanning electron microscopy, and electron probe microanalysis techniques, we identified a range of sulfide minerals (Fig. 1).

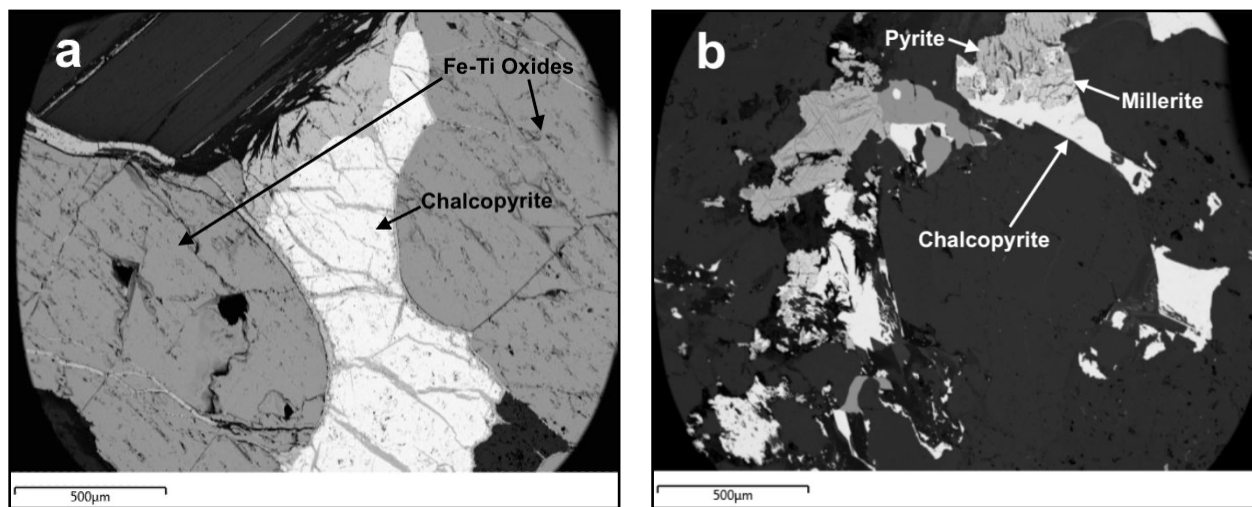


**Fig. 1 (a)** Backscattered electron (BSE) image of a chalcopyrite grain within the Longnose OUI sample L\_03. **(b)** BSE image of sulfides within the Titac OUI sample T\_45.

Our findings demonstrate that Longnose contains about 1 modal percent sulfide, while Titac contains 1-5 modal percent. Longnose and Titac are both dominated by chalcopyrite (constitutes >90% of sulfide phases), with trace bornite, sphalerite, and millerite. Titac also contains pyrite, whereas chalcocite is only found in Longnose by a similar process. We can also use trace element

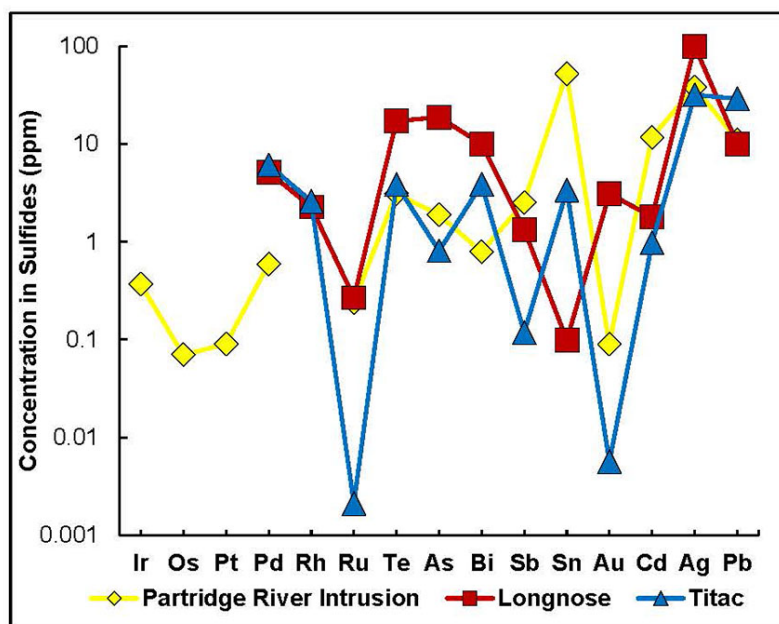


**Fig. 2.** Diagram comparing trace element concentrations between sulfides in Longnose, Titac, and within the Partridge River Intrusion (data from Samalens et al. (2017b)).

Lastly, we used laser ablation-inductively coupled plasma-mass spectroscopy to determine the trace element composition of the sulfides. Similar analyses have been done on Cu-Ni deposits in other parts of the Duluth Complex (such as within the Partridge River Intrusion) to understand their genesis. Comparing trace element composition between sulfides in these OUIs and sulfides within the Partridge River Intrusion (Fig. 2) can show us if the OUIs were formed.

compositions of our sulfides to determine whether these OUIs have a hydrothermal or magmatic origin, which is fundamental for being able to propose a genetic model.

In this study, we investigate the mineralogy and geochemistry between sulfide minerals from these OUIs and sulfides within Cu-Ni deposits in the Duluth Complex and around the world to better understand how these OUIs were formed.

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**Geology and geochemistry of the Elsie Mountain and Stobie Formations, Huronian Supergroup: Developing a chemostratigraphy to address challenges with the current subdivision**

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The Paleoproterozoic Huronian Supergroup (HSG) is a well-preserved package of supracrustal rocks deposited along the southern margin of the Superior Province between ~2.5 and 2.2 Ga. Volcanic rocks occur in the lower part of the HSG succession. In the Sudbury area, the volcanic rocks are subdivided into the Elsie Mountain (mafic metavolcanic rocks with minor felsic metavolcanic and metasedimentary rocks), Stobie (mafic to felsic metavolcanic rocks with metasedimentary rocks), and Copper Cliff Formations (felsic metavolcanic rocks). The criterion historically used to differentiate between the Elsie Mountain and Stobie Formations is the percentage of intercalated metasedimentary rocks (Elsie Mountain <15%; Stobie >15%). This presents challenges in identifying and correlating the volcanic units, especially where the Elsie Mountain and Stobie Formations are interlayered with overlying metasedimentary rocks of the Matinenda or McKim Formations; intruded by mafic rocks; and/or have undergone multiple deformation events. Based on recent mapping in the Sudbury area, a preliminary geochemical characterization of the mafic volcanic rocks of the Elsie Mountain and Stobie Fms is presented.

Mafic volcanic rocks of the Elsie Mountain Fm are divided into EMF-1 and EMF-2, which are geochemically distinct from each other and mafic rocks of the Stobie Fm. Mafic rocks of EMF-1, along with Stobie Fm, are high-Fe tholeiitic basalts. EMF-1 represent the basal lavas, but they are not the most primitive lavas as they have lower MgO, Ni and Cr and higher SiO<sub>2</sub> compared to the overlying Stobie Fm. Mafic rocks of EMF-1 and Stobie Fm exhibit similar primitive mantle-normalized trace element profiles characterized by LREE enrichment relative to HREE and negative Nb-Ta-Ti anomalies. EMF-2 mafic volcanic rocks are tholeiitic andesites with distinct primitive mantle-normalized REE profiles characterized by strongly depleted HREE. EMF-2 mafic rocks also have higher Ni and lower V contents compared to EMF-1. On a Nb/Yb versus Th/Yb diagram (Pearce element diagram), the EMF-2 mafic rocks define a distinct trend separate to that of the EMF-1 and Stobie Fm mafic rocks.

Using these geochemical criteria, synvolcanic mafic sills and intercalated mafic flows with similar geochemical characteristics to the Elsie Mountain and Stobie Fms have been identified within the overlying Matinenda and McKim Fms. This supports the interpretation that the HSG volcanic rocks in the Sudbury area are younger than those in the Thessalon area (~200 km to the west) where the volcanic rocks are disconformably overlain by the Matinenda Fm. However, there is a striking similarity when comparing data from this study with the HSG volcanic rocks in the Thessalon area. The mafic rocks of EMF-1 and Stobie Fm are comparable to an upper basalt-basaltic andesite Thessalon unit. The rocks of EMF-2 closely resemble a stratigraphically lower basalt-andesite Thessalon unit. Based on the geochemical similarity with the Thessalon volcanic rocks, similar magmatic processes and sources were likely responsible for the generation of the Thessalon, Elsie Mountain and Stobie Formation mafic volcanic rocks.

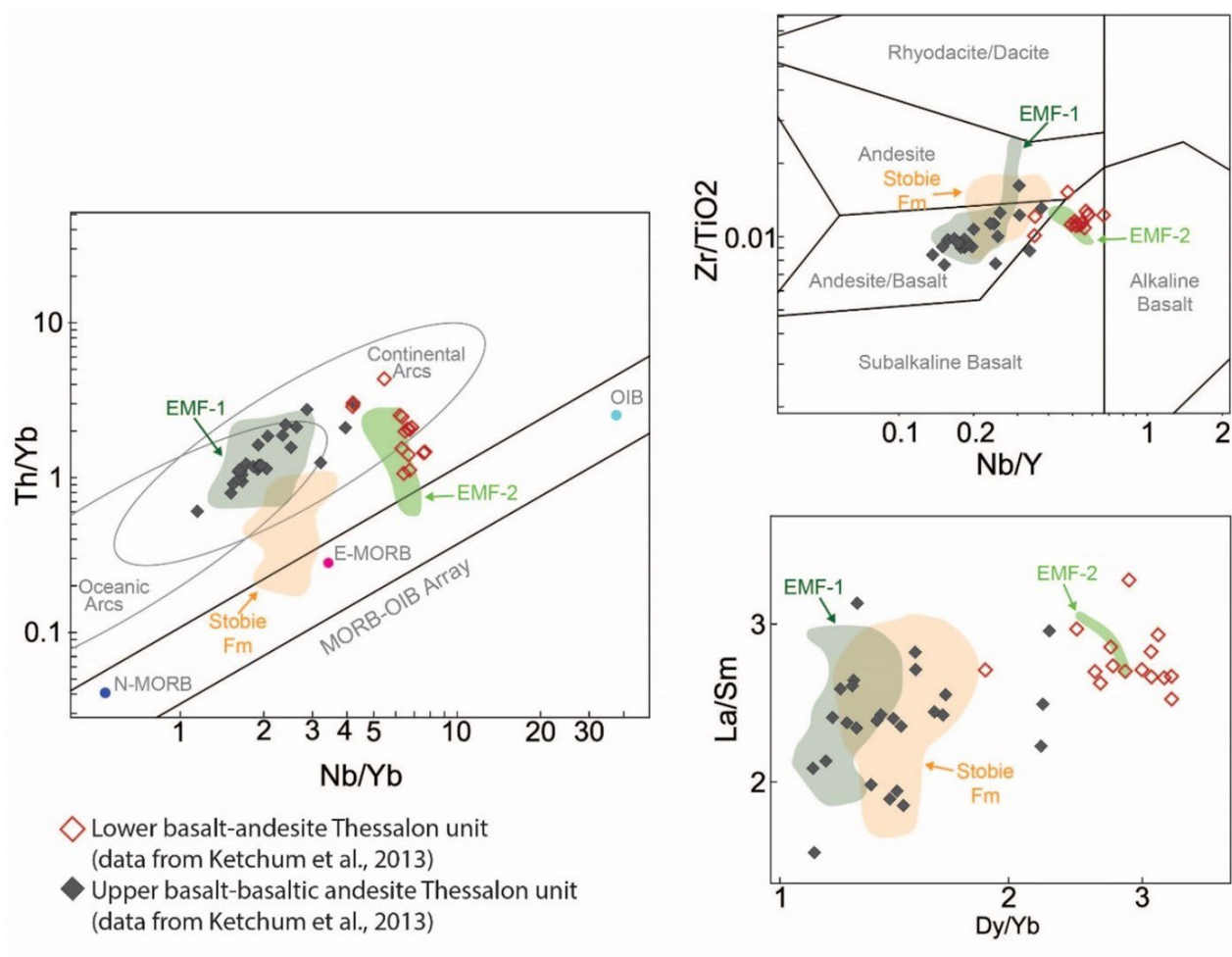


**Figure 1.** Th/Yb vs. Nb/Yb (Pearce element diagram) (A) Zr/TiO<sub>2</sub> vs. Nb/Y (Winchester-Floyd diagram) (B) and La/Sm vs. Dy/Yb (C) showing the three geochemically distinct mafic lava sequences within the Stobie and Elsie Mountain (EMF-1 and EMF-2) Formations compared to volcanic rocks of the Thessalon Formation.

Results from this study highlight that: 1) there are at least 3 geochemically distinct mafic lava sequences within the Stobie and Elsie Mountain Formations, 2) HSG volcanic rocks in the Sudbury area are intercalated with the Matinenda and McKim Formations, 3) geochemical similarity with older HSG volcanic rocks in the Thessalon area, and 4) the need for detailed geochemical characterization of volcanic units in the Sudbury area to aid in mapping and correlation.

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## **Geochemistry and mineralization of the Archean Titan (Roaring River) Intrusion, Northwestern Ontario**

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The Archean Titan intrusion, formerly known as the Roaring River mafic intrusion, is one of several layered mafic-ultramafic complexes in northwestern Ontario that are currently the focus of ongoing PGE exploration. The Titan intrusion is located ~145 km North of Thunder Bay, Ontario, in the Winnipeg River terrane of the western Superior Province and is part of the Roaring River Complex (Figure 1).

The Titan intrusion was identified as an underexplored area during a lake sediment survey in 2000 (Ontario Geological Survey). In the following five-year period, there were several periods of prospecting and soil surveys carried out in the area as well as one diamond drilling project, which aimed to determine the extent of the Titan intrusion within the Roaring River Complex, and whether or not the Titan intrusion contained economic Ni-Cu-PGE mineralization. This early exploration revealed petrologic and geochemical similarities between the Titan intrusion and the mineralized mafic-ultramafic rocks in the Lac des Iles (LDI) Complex, which lies ~60 km to the south of the Titan intrusion (Figure 1). The LDI Complex is the largest of a series of mafic and ultramafic intrusions, all within the Marmion terrane, and hosts the world-class LDI palladium mine. An unpublished U-Pb age for zircons from the Titan intrusion yielded an age of  $2690 \pm 3.2$  Ma, broadly coeval with the LDI Complex, dated at  $2689 \pm 1.0$  Ma (Heaman and Easton, 2006). Lithological and geochemical similarities, as well as the spatial and temporal association, suggests that there may be a genetic relationship between the Titan intrusion and the LDI Complex. This study seeks to evaluate the possible genetic relationship between these systems, if any, in terms of their formation, evolution, and economic potential via detailed geochemical and isotopic characterization of the Titan intrusion.

Outcrop in the area is sparse, due to the presence of pervasive glacial till and Proterozoic diabase sills (Figure 2). Samples were collected in the summer of 2021 and analyzed for whole rock and PGE geochemistry, sulfur and Sm-Nd isotope analysis, and detailed petrographic characterization, the interpretation of which is still underway. Preliminary petrography reveals that the intrusion is a mix of gabbro and norite, with little to no presence of ultramafic lithologies. Sericite-actinolite alteration is pervasive, though the level of alteration varies between samples. Sulfide mineralization is generally confined to pyrite and chalcopyrite, though inclusions of pyrrhotite are observed occasionally. Sulfide mineralization is typically fine-grained and disseminated, though larger blebs do occur (Figure 2). However, Pt and Pd values determined through whole rock geochemistry are not always consistent with the degree of sulfide mineralization observed in thin section or hand sample, suggesting that PGEs are not solely hosted within sulfide mineral assemblages. The Titan intrusion is characterized by enriched LREE's and fractionated HREE's, with negative Nb, Zr, Hf, and Ti anomalies. Geochemistry also reveals a spatial trend with higher MgO samples associated with the outer edges of the intrusion, while low MgO samples occur towards the centre. This trend does not necessarily hold for other major elements or REE's, and is the subject of ongoing research.

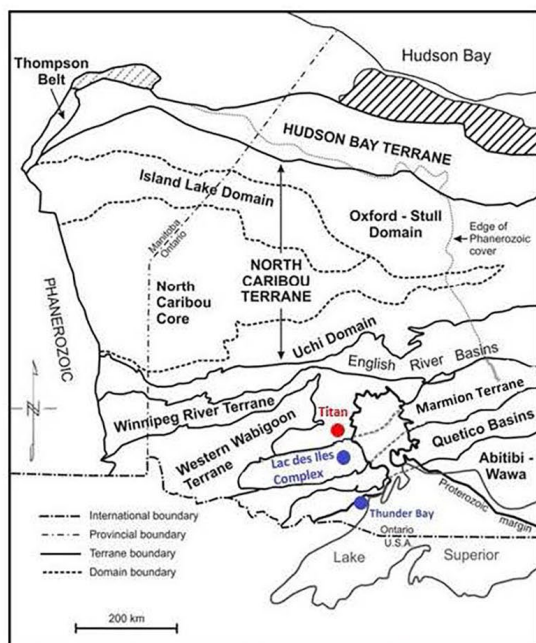


**Figure 1:** (left) A regional geology map of the western Superior Province highlighting the approximate locations of the Titan intrusion, the Lac des Iles Complex, and the city of Thunder Bay, modified from Stott et al., 2010.

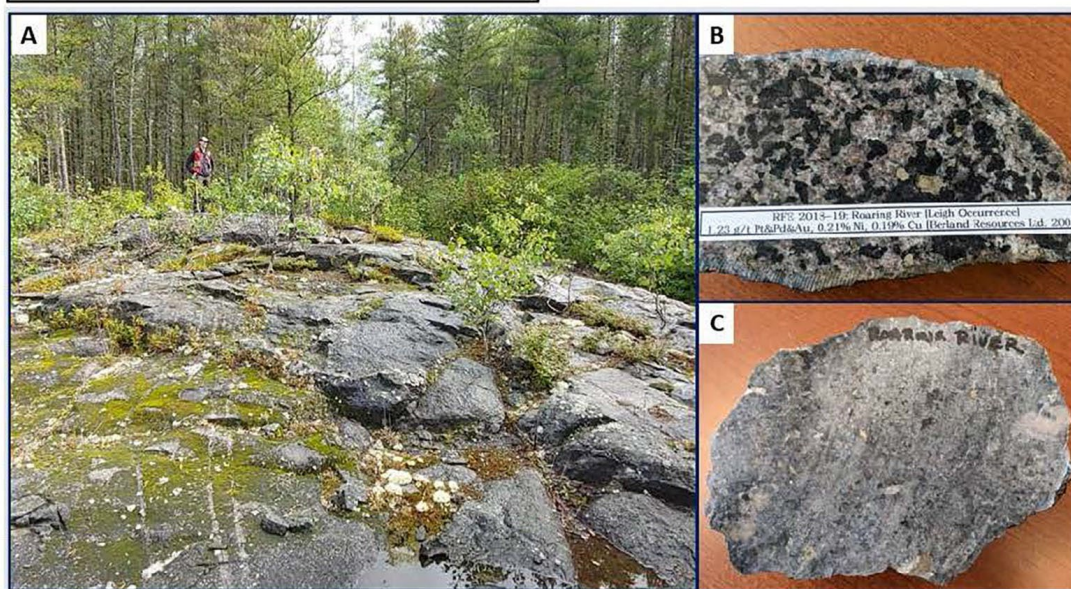


**Figure 2:** Outcrops and samples from the Titan intrusion. **A)** The L102N outcrop, just off of HWY 811. **B)** and **C)** are historical samples, showing some of the variety of textures observed within the Titan intrusion (formerly known as Roaring River). **B)** is from the Leigh occurrence and **C)** is from an unknown location. Both samples are courtesy of the Ontario Geological Survey.

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## Determining Genetic Origins of Paleoproterozoic Diamictites using Anisotropy of Magnetic Susceptibility (AMS)

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Massive, poorly-stratified, diamictites in the Gowganda Formation of the Huronian Supergroup, Ontario, Canada have varied interpretations for their origin among sedimentologists (subglacial, rainout, sediment gravity flows, etc.). This project uses anisotropy of magnetic susceptibility (AMS) to interpret the genetic origins of the Gowganda Fm. diamictites from north of Elliot Lake, Ontario (Figure 1). Deposited during the Paleoproterozoic Huronian glaciation (2.4-2.2 Ga), the Huronian Supergroup is an exceptional example of Paleoproterozoic climate fluctuations and contains the oldest widespread glaciogenic rocks on the planet (Young 1991). Although this thick succession of diamictite is believed by some to be subglacial, analysis of the AMS in the rocks can paint a more detailed picture of the processes that drove glaciation and climate fluctuation during the Paleoproterozoic, as recorded in the Gowganda Fm.

**The Gowganda Formation** is the youngest of 3 glacial cycles in the Huronian Supergroup, and crops out in northeastern Ontario, just north of Lake Huron. Like most of the conglomerate units in the Huronian Supergroup, the Gowganda Fm. includes massive, poorly sorted diamictites followed by coarsening upward successions, however the presence of bedded diamictite and deltaic deposits make the Gowganda Fm. particularly interesting (Young 1991). Interpretation of the diamictite's depositional processes differ, with some arguing that they were derived subglacially (e.g., Lindsey 1969, Mustard and Donaldson 1987, Menzies 2000) and others arguing that the diamictites were a product of density flows (e.g., Miall 1983, 1985). These hypotheses suggest different origins and thus different climatic settings and ice position during that time. In contrast with subglacially-derived diamictites, which are deposited directly under the glacier, those produced by density flows would have been deposited farther from the ice front, or even potentially not in association with glacial ice. Deciphering which hypothesis is accurate will aid in understanding glaciation and climate fluctuation in the Paleoproterozoic.

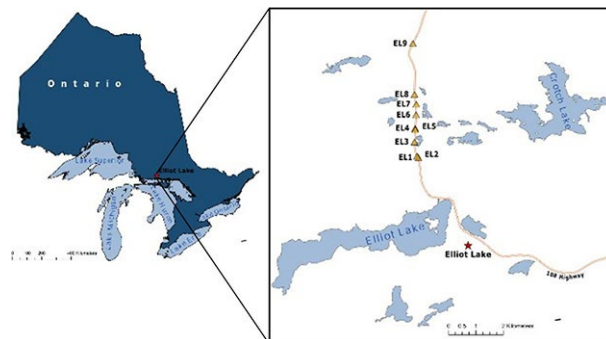


**Figure 1.** Field location. This project investigates outcrops of the Gowganda Fm. located just north of Elliot Lake along Highway 108.

**Anisotropy of Magnetic Susceptibility.** Magnetite crystals (magnetic particles) are often found in glaciogenic sediments where the host rock has been completely pulverized and the particles are able to move independently by subglacial, mass transport, sediment gravity flow, alluvial, coluvial, and/or aeolian processes (Amato 2017, Baas 2007, Hooyer 2008). These particles can be classified as pseudo-single domain (PSD), single domain (SD), or multiple domain (MD). A MD magnetic particle may have multiple directions of magnetism, each domain with a different magnetic orientation, whereas a SD particle will have only one primary direction of magnetism and is considered anisotropic. PSD domain crystals are isotropic in shape and magnetism and are not an acceptable indicator of directional flow. As elongated, anisotropic clasts are essential for determining flow direction in pebble fabrics, the magnetic orientation of SD particles (magnetic fabric), due to their anisotropy, are ideal for interpreting flow direction on a micro scale (Potter 1988, Tauxe 1998).

AMS is a product of shape anisotropy and has been used in several studies of glaciogenic and geomorphologic sediment to determine the directional force applied to those sediments by looking at the orientation of silt-sized magnetic particles in the deposits (Amato 2017, Felletti 2016, Hooyer 2008). AMS is geometrically represented by a susceptibility ellipsoid with three principal axes

( $k_1(\max)$ ,  $k_2$ ,  $k_3(\min)$ ) (Figure 2) called eigenvectors which describe a particle or packet of sediment's orientation. Additionally, each of these eigenvectors has an eigenvalue ( $\tau_1$ ,  $\tau_2$ , and  $\tau_3$  respectively) which are used to describe magnitude of the susceptibility axis and indicates shape of the ellipsoid (Oblate, Prolate, and Triaxial). Directions of these principal axes are plotted on a lower hemisphere equal area (LHEA) stereonet projection. In this way, AMS can be an indicator of flow direction and/or as an indicator of the shearing that occurred within a deposit (Amato 2017, Baas 2007, Hooyer 2008, Felletti 2016).

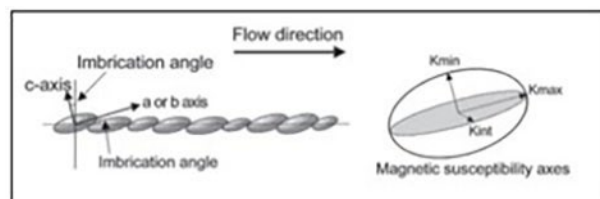


**Figure 2.** Display of eigenvectors and imbrication of magnetic susceptibility ellipsoids as how they provide evidence of flow direction.

There are four primary fabric patterns associated with different depositional processes: (1) horizontal fabric, which occurs in low energy environments where the dominant influence on particle orientation is gravity. Grains tend to fall thru suspension with their broadside perpendicular to the gravitational force (Allen 1982). When plotted on a LHEA stereonet, orientation of  $k_1$  and  $k_2$  will be distributed randomly within the horizontal plane, and  $k_3$  will be clustered near vertical. (2) Flow-aligned fabric occurs in low to medium velocity flows where grains tend to be imbricated up-current with their long axes parallel to flow resulting in a tight cluster of  $k_3$  slightly off from vertical (10-30°), and a tight cluster of  $k_1$  dipping slightly from the bedding plane. Flow-aligned fabrics show strong lineation and the imbrication of  $k_3$  eigenvectors deflected from vertical indicate flow direction. (3) flow-transverse fabric, commonly referred to as a “rolling fabric”, occur in high velocity flows, and/or sometimes sheared dispersion, and are hydrodynamically stable with their long axes perpendicular to flow resulting in a split cluster of

$k_1$  along the bedding plane, and a tight cluster of  $k_3$  imbricated up to 30° off from vertical, orthogonal to the alignment of  $k_1$ . Flow direction is indicated by the imbrication of  $k_3$  eigenvectors deflected from the vertical. (4) flow-oblique fabric occurs when the  $k_1$  axes are oriented at a significant angle to the main flow direction (Baas 2007), suggesting that they cannot be identified without a secondary flow indicator (i.e. sedimentary structure). Causes for flow-oblique fabrics have been attributed to clast interactions in a viscous flow, spatial changes in current direction, changes in flow regime, changes in substrate roughness, and soft sediment deformation (Baas 2007). For the purpose of this study, a flow-oblique fabric is defined as when the  $k_1$  and  $k_2$  axes are oriented at ~45° from the direction in which the  $k_3$  is deflected from the vertical (Amato 2017).

**Expected Results.** The diamictites of the Gowganda Fm. have a debatable origin and have been attributed to different sedimentary origins (e.g., Lindsey 1969, Mustard and Donaldson 1987, Young 1991, Menzies 2000, Miall 1983, 1985). This project aims to test the possible origins of these diamictites through examination of the magnetic fabric of the diamictite's fine-grained matrix. Through AMS analysis, it is possible to identify flow direction be it alluvial, coluvial, aeolian, or subglacial, and to identify possible shearing action that occurred during and following deposition. Any magnetic fabric that is directionally inconsistent in the formation could potentially be considered to have been produced in a manner other than subglacially.

In the larger picture, deciphering between subglacially-derived diamictites and those produced by other processes not only provides a more detailed interpretation of depositional environment, but may lead to a more comprehensive understanding of Paleoproterozoic climatic change. The presence of bedded diamictites in the middle to upper Gowganda Fm. are particularly interesting. Identified as subglacial by Young (1991), evaluation of these diamictites may aid in identifying processes of deposition of the Gowganda Fm.

## **Gold Fingerprinting: Inspiration, project overview and method development**

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Throughout the history of gold deposit research, many mineral proxies (e.g., quartz, pyrite, etc.) have been used in place of gold to interpret gold-forming processes and discriminate among deposit types. Mineral proxies are problematic in most cases as their genetic relationship to high-grade gold is not definitive. For example, almost all visible gold in hand specimen from deposits throughout Ontario is hosted in fractures that crosscut quartz (Hastie et al., 2020) making the use of this quartz to infer anything about the formation of late visible gold inappropriate. Overall, the use of these proxies has led to an incomplete understanding of the elements truly associated with gold and the formation of gold deposits. Advances in methods such as laser ablation inductively-coupled plasma mass spectrometry (LA-ICP-MS) and atom probe tomography (APT), represent powerful tools when used in conjunction with more traditional methods such as electron microscopy using energy-dispersive spectrometry (SEM-EDS) and electron microprobe analysis (EMPA) to analyze gold directly, allowing direct evidence for true Au-elemental associations or “fingerprints” to be determined.

The Gold Fingerprinting project is a collaborative effort involving the Ontario Geological Survey (OGS), the Royal Ontario Museum (ROM) and the Metal Earth Initiative at Laurentian University. The project uses a rigorous set of methods, from sample preparation to innovative analysis, to characterize the chemistry of gold. With these methods, an assessment of the elements within gold from significant deposits across Ontario, Canada, and the world is being undertaken and data obtained from this project will be used to create a freely available global gold database as well as digital map data for the province of Ontario. Herein, we present an overview of the project that includes best-practice sample preparation, an examination of optimal operating conditions and ablation characteristics for LA-ICP-MS, a protocol for the use of in-house and international reference materials, and highlights for possible metallogenic differences by region in Ontario using the chemistry of gold. More specifically the Gold Fingerprinting database will provide a baseline to assess the critical processes related to gold endowment, deposit formation and provenance, and improve our understanding of gold for exploration, metallurgy, archeology, and forensic science.

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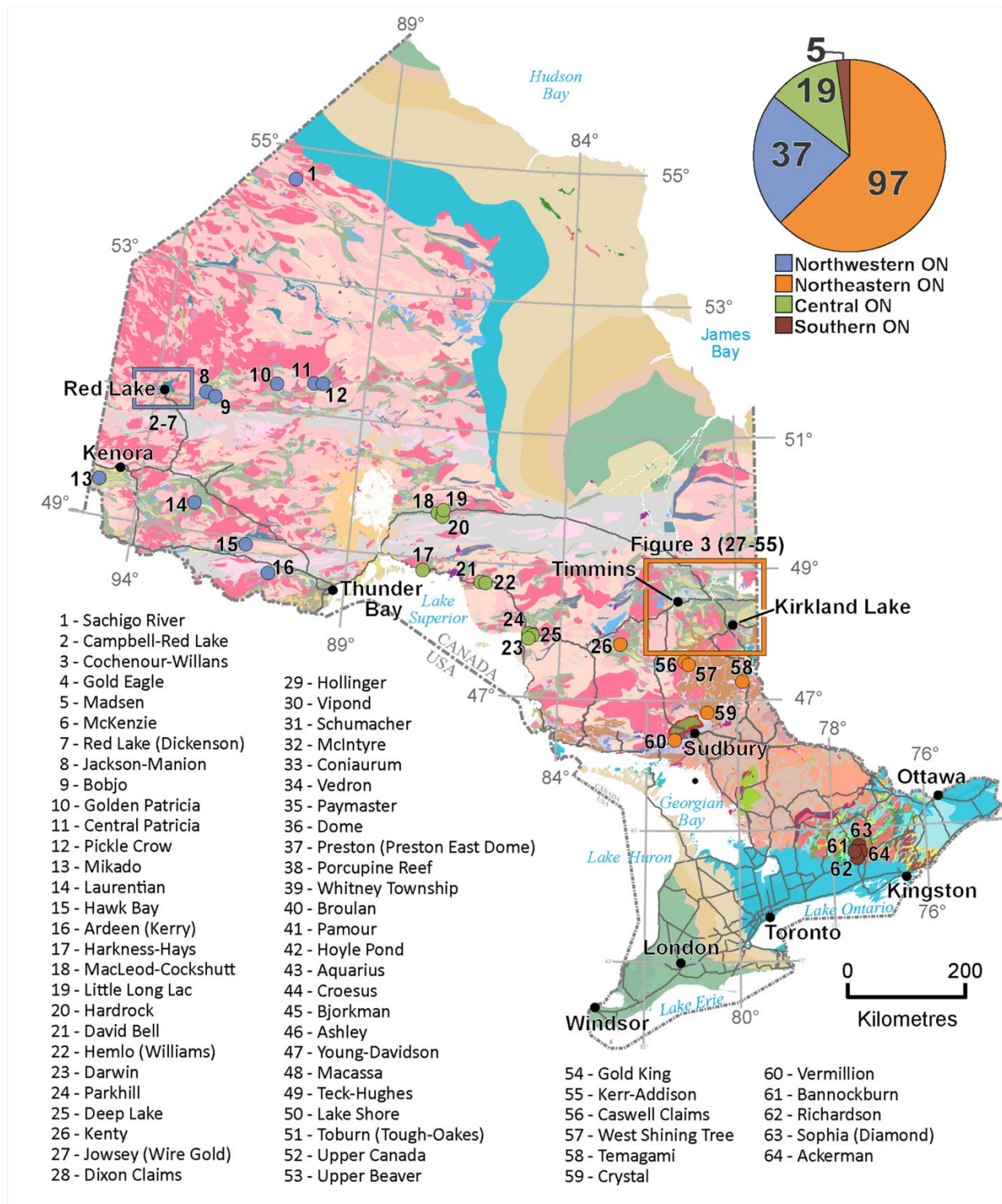


**Figure 1.** Geological map of Ontario, with simplified bedrock geology units from Ontario Geological Survey (2011), displaying the location of gold samples as of October 2021 (from Melo-Gómez et al., 2021). The pie chart in the upper right of the figure shows the numbers of analyzed samples per geographical areas; the colours used in this chart are also used for the sample location dots.

## **Preliminary petrographic and geochemical data for potential source rocks for sediment-hosted stratabound copper deposits in the Lake Superior portion of the Midcontinent Rift**

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Copper for sediment-hosted stratabound Cu deposits like White Pine and Copperwood, MI, almost certainly comes from the nearby sedimentary rock, and, for these deposits evidently comes from downsection (Brown, 1971). The Copper Harbor Conglomerate (CHC) immediately underlies ore at White Pine and Copperwood. In these and other deposits of the type, underlying rocks are fine-to-coarse clastic red beds which may have been mineralogically and chemically altered in the metasomatism that mobilized Cu. Over years of study, source rocks for deposits in the Belt Supergroup, MT-ID-BC, were determined to be former red beds that (1) are Na-rich due to abundant albite, (2) are Ca-poor compared to other feldspathic metasediments, (3) contain scattered traces of barite, and (4) form a low-Cu geochemical population among the Belt's Ravalli Group rocks (Hayes, 1990; Hayes et al., 2015). Albite zone rocks form extensive volumes on thrust plates west and east of the Western Montana Copper Sulfide Belt and occur along both walls of ore-fluid-feeding growth faults below the Spar Lake and Montanore deposits. These Cu-source-rocks in the Belt were first identified by geochemical studies (Connor et al., 1981) and later by combined petrologic and geochemical studies (Hayes, 1990).

Cu-source-rocks have yet to be identified around White Pine and Copperwood deposits. For this study we used the same methods as in the Belt Basin to search for such rocks in a regional study of the CHC in the Lake Superior portion of the Midcontinent Rift. The presence of altered copper-source-rocks and nearby reduced facies host rocks somewhere in the vast area of the Midcontinent Rift where the CHC and Nonesuch Fm. equivalents are covered might identify a mineralizing system which would be a better guide to high mineral potential than the mere presence of favorable host rocks that are already known at places along the Rift.

Twenty-nine regionally spaced CHC core samples were analyzed for major, minor, and trace elements by ICPMS and studied in polished thin sections and by electron microprobe (EMP). Samples came from Wisconsin Geological and Natural History Survey, Northern Michigan Geological Repository, and Highland Copper Co. One sample came from Jeff Mauk.

Eleven CHC petrologic samples contain complexly variable clasts unexpectedly dominated by rhyolites that went through varying changes, diagenetic and, locally, metamorphic, across the region. Clasts from the underlying Portage Lake Volcanics are present, but they constitute less than 20 volume-percent (vol-%) of detritus in all studied samples. Monomineralic quartz and feldspar clasts make up less than 40 vol-%. Many other clast types occur locally or in traces.

Diagenetic and metamorphic minerals observed include titanite (sphene), quartz, laumontite, pumpellyite, epidote, hematite, chlorite, albite, and calcite. Most CHC rocks have up to 5 vol-% ilmeno-magnetite clasts along with rare ilmeno-hematite, recognizably from igneous sources. The iron-titanium-oxides (Fe-Ti-ox) have been variably oxidized with magnetite preserved in Ashland Basin samples, but elsewhere all magnetite is altered to hematite. Ilmenite is more widely preserved. Authigenic titanite includes (1) replacements of ilmenite lamellae in Fe-Ti-ox clasts, (2) rims on Fe-Ti-ox clasts, (3) pore-lining cements, and (4) clusters of 0.1 X 0.05 mm euhedral crystals in a sample from 24 m below White Pine ore. CHC samples beneath both White Pine and Copperwood have notable quartz overgrowth cements. Samples from along the southern basin

margin appear to record diagenesis that proceeded to metamorphism. Those samples have probable pumpellyite, and some have epidote. Four samples contain unique pseudomorphs of hematite after an earlier isometric mineral, likely magnetite by comparison with skeletal cruciform magnetite illustrated by Haggerty (1976, p. Hg-107). Hematite pseudomorphs of cruciform magnetite are found below White Pine, Copperwood, and Highland Copper Co.'s JBY prospect located 85 km northeast from White Pine, 6 km (3.8 miles) northwest of Calumet, MI, and 1.2 km from Lake Superior. Hematite after cruciform magnetite is locally Cu-rich, with up to 0.5 weight-percent (wt-%) Cu by electron microprobe (EMP) analyses, though in other cruciform hematite, even from the same sample, Cu is below detection. The most important observation may be strong albite alteration in three samples from JBY prospect that underlie basal mineralized Nonesuch Fm. (rock containing about 0.5 wt-% Cu, as chalcocite (Highland Copper Co. corehole log)). Samples that come from 7 m, 63 m, and 92 m stratigraphically below the Nonesuch have the following Na/K molar ratios, respectively: 3.04, 3.42, and 5.56. Albite increases downward. In the deepest sample volcanic pebbles with former plagioclase phenocrysts have been altered. Pebble textures approach trachytic, so the phenocrysts would have originally been, perhaps, labradorite. Phenocrysts and most other feldspar in the rock is now pure albite. Yet, this rock does not match the Cu-source-rock of the Belt, because it contains 194 ppm Cu, anomalously high rather than depleted relative to background. EMP examination of JBY albitic rock shows that its Cu is either as native copper within late calcite or is in chalcocite associated with laumontite. It appears that, after early albitization and Cu depletion, Cu was added back, probably at the time of the Calumet native copper mineralization event. At White Pine such mineralization is called "second-stage" (Mauk et al., 1992).

In summary, Cu-source-rocks for Highland Copper's JBY sediment-hosted stratabound copper prospect have very likely been identified. Albitization increases down-sectionward at JBY, but all the rocks have also been slightly overprinted by second-stage Cu mineralization of the Native Copper District. The inability to sample outcrops near White Pine and Copperwood has not yet allowed a proper test for similar rocks near these deposits. The study generally supports the concept that finding an area where both host (Nonesuch-corollary) and albite-altered Cu-source-rocks (Copper Harbor-corollary) are nearby one-another is workable and could prove useful southwest along the Midcontinent Rift where the Keweenawan rocks are covered.

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## Characterizing Late Wisconsinan Rainy Lobe Till from the Hudson Bay Lowlands to SW Minnesota: Insights on provenance and ice sheet behavior during Late Wisconsin glaciation

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The Rainy lobe emanated from the Labradoran sector of the Laurentide ice sheet and reached its maximum limit in SW Minnesota. The ice advanced to its maximum limit in southwestern Minnesota well prior to the Last Glacial Maximum, possibly as early at 27 ka BP and retreated into Ontario by 17.9 ka BP (Mooers and Lehr, 1997; Lowell et al., 2009). In Minnesota, the advance and retreat is recorded by a nearly continuous till sheet, which is exposed in the Wadena, Brainerd, and Toimi drumlin fields, which are composed of the Hewitt, Brainerd, and Independence tills, respectively; this till sheet correlates with similar deposits in the Hudson Bay Lowlands (Fig.1). Till of this Late Wisconsin glacial cycle exhibits dramatic spatial and temporal changes in provenance. The Hewitt till of the Wadena Drumlin field (Fig. 1) contains abundant carbonate and greywacke from the Omarolluk formation (omars) (Berthold, 2015; Prest et al., 2000). Omars have been used extensively in ice flow reconstructions due to their identifiable characteristics and the limited outcrop exposure in Hudson Bay (Shilts, 1980). The Brainerd and Independence tills in central and NE Minnesota (Fig. 1) have significantly less carbonate and omars, and are dominated by locally derived lithologies from NE Minnesota and adjacent Ontario, including granite, greenstone, iron formation, felsite, and gabbro. The observed change in lithology reflects changes in the mean transport length of the till. The mean transport length is the average distance of transport defined by the indicator lithology abundance (Larson and Mooers, 2004). The Hewitt till has a mean transport length of > 1000 km, whereas the Brainerd and Independence tills have mean transport lengths of approximately 400 and 100 km, respectively (Berthold, 2015).

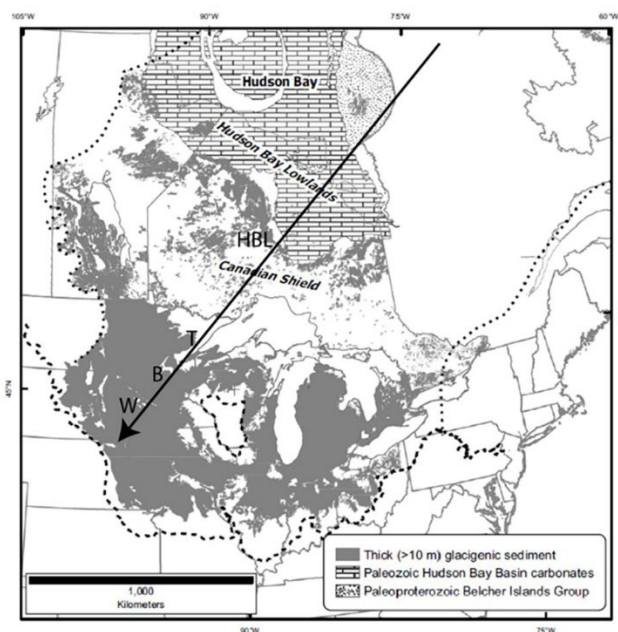


**Figure 1:** Flow path of the Rainy Lobe during Late Wisconsinan Glaciation. Hudson Bay Lowlands (HBL), Toimi drumlin field (T), Brainerd Drumlin field (B), Wadena drumlin field (W). Modified from Larson (2008).

Larson (2008) proposed that as the Rainy lobe advanced early in the last glacial cycle, a continuous till sheet composed of sediment from Hudson Bay and the Hudson Bay Lowlands extended to SW Minnesota. As the ice approached its maximum limit, much of this till sheet was eroded exposing Canadian Shield bedrock along the central portion of the flow path (Fig. 1). Later phases of the Late Wisconsin Rainy lobe therefore reflect increased proportions of shield lithologies.

To evaluate Larson's (2008) model of changing provenance, twenty-eight samples were collected along a transect from SW to NE Minnesota, which includes the Hewitt, Brainerd and Independence tills. Additionally, six till samples were collected from the Hudson Bay lowlands in an area immediately south of the Paleozoic carbonate platform limit. The <64 micron fraction was analyzed to measure elemental abundance using a four acid digestion process (total carbon was also included in the analysis to obtain carbonate percentages). Fine fraction geochemistry has proven to be an excellent tool for discriminating till provenance (Gowan, 1998).

Results are summarized on Fig.2, where iron, magnesium, and calcium provide a proxy for the geochemical contributions of limestone, dolomite, and Shield rocks that comprise the till; increasing iron reflecting increased local incorporation of shield rocks. Five are identified. The Hewitt till (and the Granite Falls till (Matsch, 1972)) in far SW Minnesota has the longest mean transport length (Berthold, 2015) and in the model of Larson (2008) would reflect an origin in Hudson Bay. Successively younger deposits, Hewitt till in central Minnesota and the Brainerd and Independence tills, plot progressively toward the iron apex (Fig. 2). However, samples from the

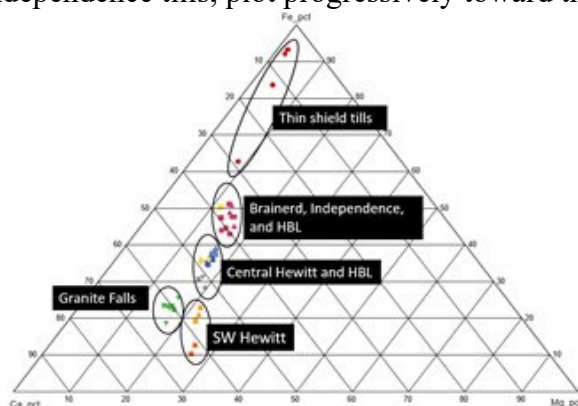


**Figure 2.** Iron-calcium-magnesium ternary plot of sampled tills.

Hudson Bay lowlands are similar to the Hewitt till of central Minnesota. Results of the geochemistry support the conclusion of Berthold (2015) and Larson (2008) that the Hewitt till of SW Minnesota has a mean transport length of > 1000 km, reflecting an origin in Hudson Bay. Geochemistry of the Brainerd and Independence tills reflect increasing incorporation of Shield bedrock. However, till from the Hudson Bay Lowlands is similar geochemically to the Hewitt till of central Minnesota.

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**Calibration of the timing and magnitude of a two-stage Grenvillian inversion of the Midcontinent Rift using U-Pb geochronology and clumped isotope thermometry on the Douglas Fault, WI**

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The late Mesoproterozoic Midcontinent Rift accumulated a thick succession of rift-related volcanic and clastic rocks on the North American craton during an interval of rapid plate motion that led to the Grenvillian Orogeny (Swanson-Hysell et al., 2019). It has been proposed that far-field effects of Grenvillian orogenesis caused rift cessation and crustal-scale inversion within the rift (Cannon, 1994). However, poor age constraints have contributed to a range of tectonic interpretations, including post-Grenvillian inversion (Malone et al., 2016). In a recent study on the Keweenaw Fault in northern Michigan, two stages of inversion have been linked to Ottawan (ca. 1090–1030 Ma) and Rigolet (ca. 1010–980 Ma) phases of Grenvillian orogenesis (Hodgin et al., 2022). Here, we test the two-stage Grenvillian inversion model on another segment of the Midcontinent Rift in northern Wisconsin, where the Douglas Fault, which accommodated up to 20 km of shortening (Nicholson et al., 2004), juxtaposes the ca. 1100–1090 Ma rift-related Chengwatana Volcanics in the hanging wall with post-rift sandstone of the Bayfield Group in the footwall. To constrain the timing of fault movement, we used paired LA-ICP-MS and CA-ID-TIMS U-Pb geochronology to date detrital zircon samples from the footwall and paired LA-ICP-MS U-Pb geochronology and clumped isotope thermometry on vein calcite from the Douglas Fault zone at Pattison State Park and Amnicon Falls State Park in northern Wisconsin.

Three Bayfield Group detrital zircon samples from the footwall of the Douglas Fault each yielded CA-ID-TIMS maximum age constraints between 1030 and 1020 Ma. An additional detrital zircon sample from the Bayfield Group located farther from the fault, yielded a maximum age of ca. 995 Ma. These results support correlation of the Bayfield Group with the <993 Ma Jacobsville Sandstone (Hodgin et al., 2022), suggesting that deformation of the Bayfield Group in the footwall of the Douglas Fault could have also occurred during the ca. 1010–980 Ma Rigolet Phase of the Grenvillian Orogeny. This interpretation is further supported by the occurrence of sandstone dikes that penetrate basalt in the hanging wall of the Douglas Fault and cross-cut quartz and calcite veins. The composition of the sandstone dikes is identical to the Bayfield Group sandstone in the footwall, and the dikes are interpreted to have been injected into the basalt during thrust emplacement, which must have occurred prior to lithification of the sandstones and therefore soon after deposition.

Earlier motion on the Douglas Fault is constrained by vein calcite that precipitated within the hanging wall. One of these fault-bound vein calcite samples yielded a precise U-Pb isochron date of ca. 1050 Ma and clumped isotope formation temperatures of ~50°C. These formation temperatures from the hanging wall are compared to ~30°C results from vein calcite that precipitated along the fault plane separating Chengwatana Volcanics and Bayfield Group sandstone. Assuming a geothermal gradient of ~25°C/km and surface temperatures of ~10°C, we interpret these data to indicate that the dated calcite in the hanging wall was within 2 km of the surface prior to final inversion of the Douglas Fault. This interpreted shallow depth is consistent with a 1 to 2 km maximum thickness of the Bayfield Group in the footwall (Nicholson et al., 2004),

and indicates that the majority of the ~20 km of shortening on the Douglas Fault took place during the Ottawa Phase of the Grenvillian orogeny. These results are consistent with estimates of Ottawa shortening on other segments of the Midcontinent Rift (Cannon et al., 1993), which suggests that our calibration of the timing and magnitude of shortening on the Douglas Fault is broadly representative of Midcontinent Rift inversion, which we interpret was driven by far-field effects during both the Ottawa and Rigolet phases of the Grenvillian Orogeny.

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## Geology and Geochemistry of Midcontinent Rift System Rocks, Porphyry Island, northern Lake Superior, Ontario

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Basalt flows dip shallowly (~8°) to the southeast. Sheet-like, individual flows vary from 10 cm to perhaps greater than 5 m in thickness. Thicker flows may comprise a number of individual flow units, each denoted by a vesicular / amygdaloidal base and top; flow units are commonly separated from one another by thin, rubbly layers. Large, rough outcrops lacking obvious flow contacts and other features may represent the cores of even thicker flows that grew by continued inflation. Pahoehoe toes, pipe amygdules and amygdule cylinders were also noted.

Gabbro, diabase and related mafic dykes that intrude the volcanic flows are predominantly east-striking and typically range in thickness from 1 to 15 m. They are distinguished from smaller (~30 to 50 cm), fine-grained, sinuous, mafic dykes with various orientations that likely are feeder dykes to overlying volcanic flows. Mafic dykes are characterized by well-developed chilled zones along their edges and blocky to columnar joints developed parallel to the dyke contacts.

A heterolithic breccia dyke, described as granophyre by Tanton (1931), intrudes basalt flows. It has a fine-grained, grey matrix which hosts abundant fragments of coarse-grained, altered, brick-red, felsic igneous rocks, and a variety of finer-grained clasts. Three initial zircon fractions from this unit yielded three relatively sharp, clear, elongate prismatic single grains of good quality (precise and concordant) which returned old and slightly different Archean ages. Two are concordant at  $2805 \pm 2$  Ma, while a third is concordant at  $2729 \pm 3$  Ma. These inherited grains may have been either recycled from partially melted Archean basement, or perhaps were detrital grains from brecciated and partly disaggregated, Mesoproterozoic (*ca.* 1.4 Ga) Sibley Group sedimentary rocks that underlie Osler Group rocks. The zircons do not seem to show any signs of younger (*ca.* 1100 Ma) overgrowths, or secondary Pb-loss associated with MRS reheating.

The magnetically reversed, stratigraphically lowest lavas (*ca.* 1108-1105 Ma) of the ~3 km thick Osler Group are primitive, Mg-rich tholeiites that continue upward into lower-Mg tholeiites (Keays and Lightfoot, 2015). Trace element geochemistry suggests that the basaltic flows and sinuous dikes on Porphyry Island are part of the Lower Suite of the Osler Group (Hollings et al., 2007), characterized by moderate LREE enrichment ( $\text{La}/\text{Sm}_n = 2.1\text{-}2.5$ ), fractionated HREE ( $\text{Gd}/\text{Yb}_n = 3.7\text{-}4.1$ ) and lacking pronounced Th enrichment. The mafic dikes are characterized by less enrichment in LREE ( $\text{La}/\text{Sm}_n = 1.1\text{-}2.1$ ) and flatter HREE ( $\text{Gd}/\text{Yb}_n = 1.6\text{-}1.7$ ) and can be divided into two suites based on the Th/Nb characteristics. Dikes PY-05, -11, -12 and -21 have elevated Th contents, producing high Th/Nb ratios (0.2-0.3), and pronounced negative Nb anomalies, whereas PY-18 and -22 are characterized by Th/Nb ratios of 0.10-0.13 and lack the strong negative Nb anomalies (Figure 1). This suggests that the history of dike magmatism and emplacement on the island may be quite complex.

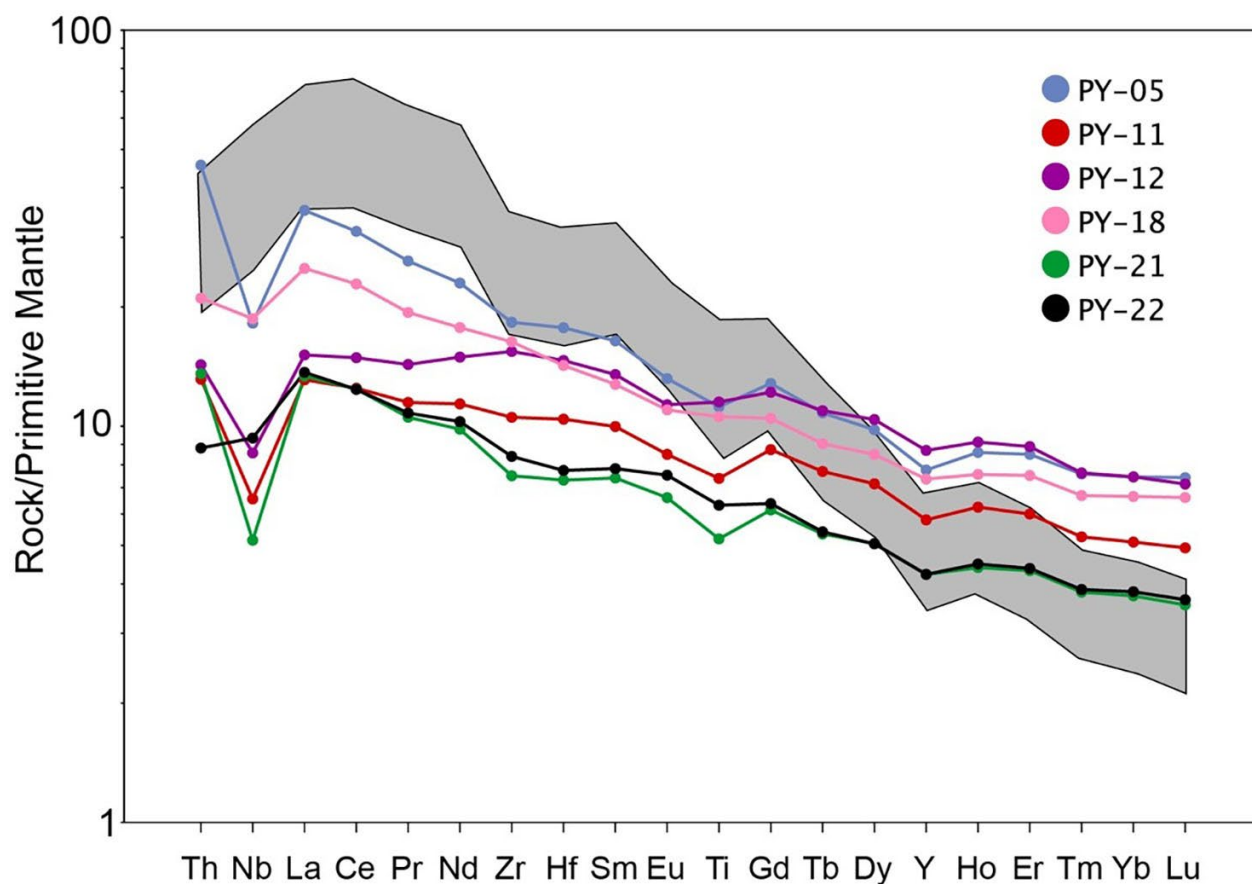


**Figure 1.** Primitive mantle-normalized trace element plot for Porphyry Island mafic dyke samples (numbered); the grey, shaded area is the field for basalt samples collected on the island.

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## **Fluid inclusions in euhedral calcite crystals from the Quincy Mine, Keweenaw Peninsula native copper district, Michigan**

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Michigan's Keweenaw Peninsula is well known for hosting the largest accumulation of hydrothermal native copper anywhere in the world. The lack of fluid inclusion studies in this district can be attributed to Livnat (1983) who concluded that, it was futile to study fluid inclusions (FI) since in virtually all of his many samples they were poorly suited because of small size, difficulty in classification, or post-entrapment changes. We reasoned that euhedral calcite crystals that freely grew into vugs would provide the best opportunity to identify primary or pseudosecondary FI as these crystals may have been subjected to minimal post emplacement fracturing. We selected calcite crystals with inclusions of native copper from the Quincy Mine.

In this study, FI were carefully classified as primary, pseudosecondary, secondary or unknown using criteria of Goldstein and Reynolds (1994). FI along a fracture that terminated within the crystal at a growth zone were classified as pseudosecondary. Primary FI were those that occurred along growth zones and were isolated from other FI or had a negative crystal shape. Cathodoluminescence was used to identify growth zones in the calcite crystals and help group the mineral textures into main-stage that resulted in precipitation of native copper and late-stage which lacks native copper. Late-stage is not discussed here.

Homogenization temperatures for individual main-stage FI that could be classified with reasonable certainty as primary or pseudosecondary ranged from less than 50°C to 166.0°C (Figure 1). For most of these FI the corresponding final melting temperature, salinity, was also determined. The homogenization temperatures determined from euhedral calcite crystals from the Quincy Mine are similar to those determined by Livnat; Livnat did not determine salinity. The trapping temperature or temperature of precipitation depends on the homogenization temperature, fluid density/salinity, and the pressure. The estimated trapping temperature (precipitation temperature) of main-stage calcite from the Quincy Mine is about 225°C based on several lines of reasoning (Bodden, 2019). Potter (1997) has provided a series of pressure correction diagrams for salinities up to 25 equiv. wt. %. A temperature of 140.0°C, near the maximum, and salinity of ~10 wt. % NaCl equivalent is used to correct the homogenization temperature to a presumed trapping temperature between of 210°C and 260°C. The pressure correction to the expected trapping temperature requires pressures between 75 MPa and 140 MPa (Figure 2). Based on the stratigraphic thicknesses from a USGS cross section through the No. 6 shaft of the Quincy Mine, lithostatic pressure is calculated to be around 140 MPa. The FI pressure correction required for a reasonable trapping temperature is consistent with other estimates of pressure of between 50 to 400 MPa (Kelly, 2020). This suggests that the FI are in fact primary or pseudosecondary, however the large pressure correction required negates the value of the homogenization temperatures.

Salinity ranged from 5.0-54.9 NaCl equiv. wt. % for main-stage calcite and was more consistent within FI groups than homogenization temperatures. It is likely that Ca ions were dominant over Na as many of the higher salinity FI had final melting temperatures well below what is possible for the NaCl system. The variability in salinity can be explained by mixing of ore-bearing fluids with meteoric waters.

The results of this study demonstrate that careful study of FI from the native copper deposits can yield valuable insight into the nature of the hydrothermal fluids.

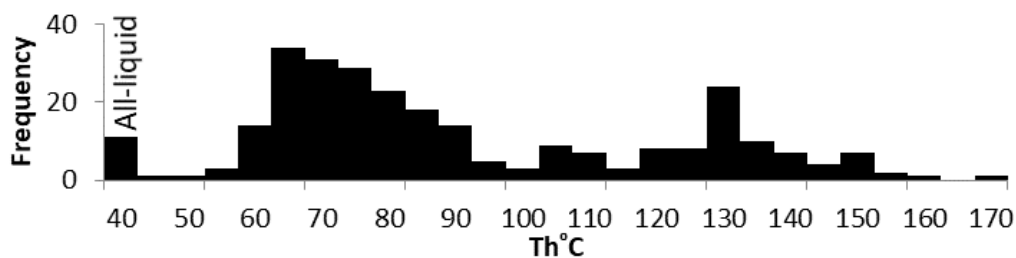


**Figure 1:** Homogenization temperatures for individual main-stage calcite from the Quincy Mine. A fluid inclusion with no vapor bubble indicates temperatures of less than 50.0°C and these are shown as between 35°C and 40°C.

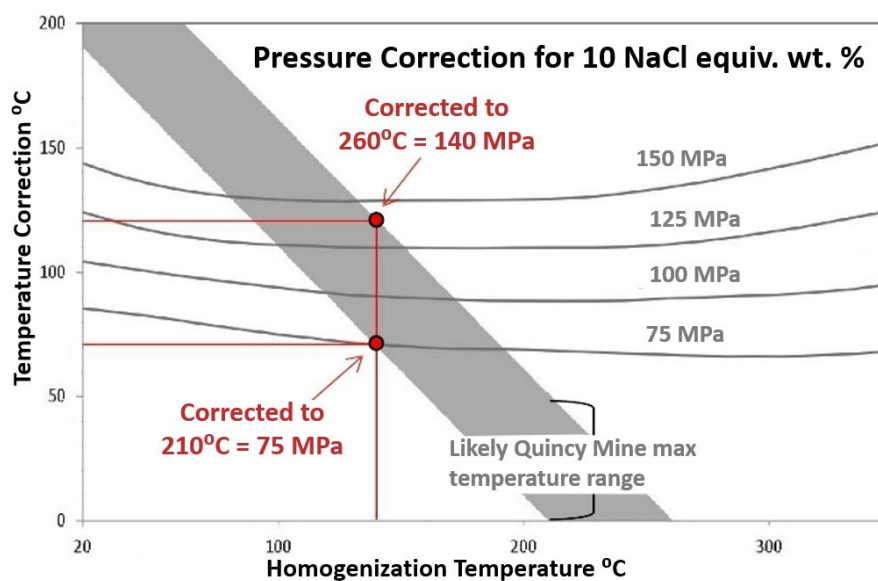


**Figure 2.** Pressure correction for homogenization temperature of 140.0°C and a calculated salinity of ~10 NaCl equiv. wt. % which represents the high homogenization temperature. Modified from Potter (1977). Shows the likely Quincy Mine precipitation temperature range.

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**Continental-scale sediment dispersal of the Mesoproterozoic Baraboo Interval quartzites in the southern Lake Superior Region, USA**

**Aidan Krieger, David H. Malone, John Craddock, Steven D.J. Baumann, Shawn J. Malone and Daniel Holm**

POSTER, No abstract provided

## **Slip Kinematics of the Hancock Fault in the Midcontinent Rift System, Keweenaw Peninsula, Michigan**

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The Hancock fault on Michigan's Keweenaw Peninsula is less well known than its much larger counterpart, the Keweenaw fault, to which it connects (Fig. 1). Both faults are contained within the Midcontinent Rift System (MRS) that formed about 1.1 billion years ago when a major rifting event split the ancient North American continent in the Lake Superior region. The rifting event caused eruption of large volumes of basaltic magma, ending with the Portage Lake Volcanics (PLV) that have an exposed thickness of 3-5 km along the Keweenaw Peninsula (Cannon and Nicholson, 2000). The most common interpretation of the Keweenaw fault is that it began as a normal fault of the MRS and then inverted to become a reverse fault during a post-rift compressional event, hypothesized to be the Grenville Orogeny (Cannon, 1994; Bornhorst, 1997). Another interpretation is that the Keweenaw and Hancock faults are parts of a detached fault system initiated during post-rift compression (DeGraff and Carter, 2022).

Previous interpretations until a few years ago imply only dip slip along the Keweenaw and Hancock faults (Fig. 1). Recent surface mapping and measurements of fault slip lineations, however, reveal a significant component of right-lateral strike slip on the Keweenaw fault system near its northeastern end (Tyrrell, 2019; Mueller, 2021). In apparent contradiction, the Hancock fault is shown on published maps with apparent left-lateral offset of units across it (Fig. 1) (Cannon and Nicholson, 2001). We have initiated work to clarify the slip kinematics of the Hancock fault in relation to the Keweenaw fault in an attempt to resolve the apparent contradictions and relate both faults to their causative tectonic regime. The work involves measuring and analyzing fault slickenlines along the Hancock fault in the historic Quincy Mine adit, and it complements detailed mapping with submeter horizontal accuracy along both faults. We used the FieldMove Clino app as well as a Brunton compass to make the structural measurements, and Stereonet and FaultKin freeware to plot and analyze the data (Cardozo and Allmendinger, 2013).

Although the project is still underway, both in the adit and on the surface, some preliminary results are available. Fault surfaces and slickenlines along the Hancock fault in a northeast drift off the Quincy Adit (Fig. 2) have been measured and sense of slip has been determined where possible. Circular histograms of slickenline rakes associated with the Hancock and Keweenaw Faults show that the Hancock fault has more dip-slip than strike-slip compared to the Keweenaw Fault (Fig. 3). Based on our measurements so far, the Hancock Fault also shows more right lateral movement than left lateral movement. This contrasts with our current Keweenaw Fault data, in which left lateral movement dominates. Additional fault slip data will be collected along the Hancock fault southwest of the main adit to complete the underground data acquisition, at which time final analyses and results will be provided.

### **Acknowledgments**

Thanks to the ILSG Student Research Fund for helping fund this project. Also, thanks to the USGS EDMAP Program for funding complementary work on the Keweenaw Fault. Additional thanks goes to Breanne Heusdens for fieldwork assistance.

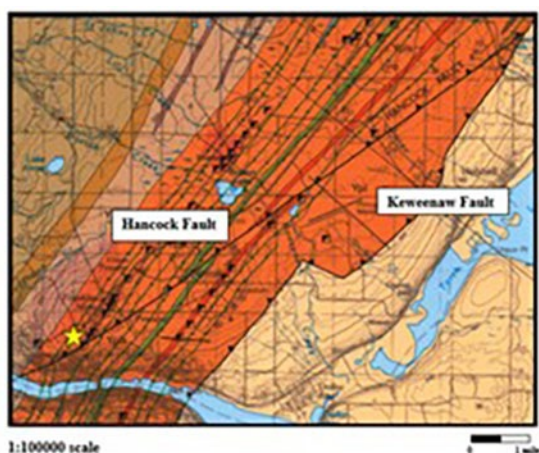


**Figure 1.** Geologic map of study area showing the Hancock and Keweenaw faults (Cannon and Nicholson, 2001). Star denotes the location of Quincy Adit.

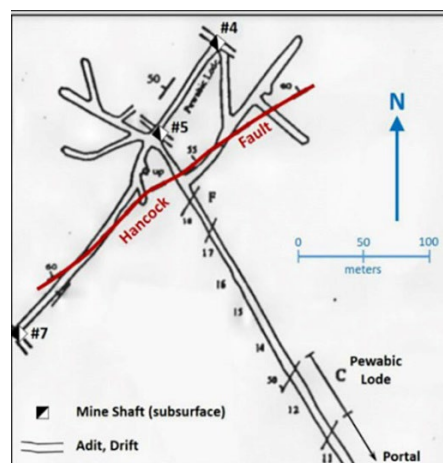
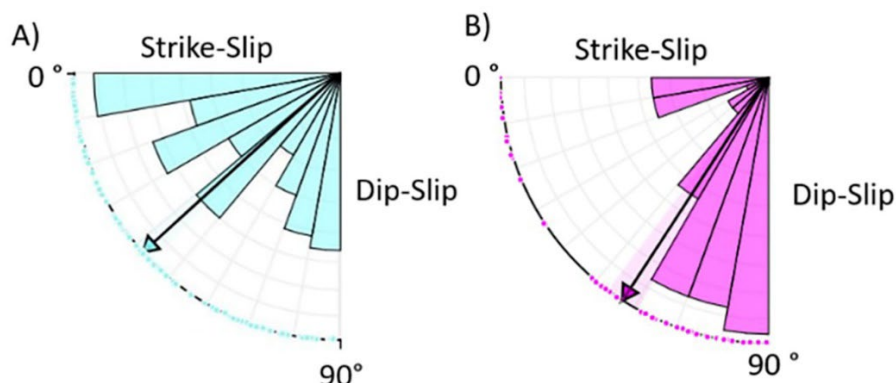


**Figure 2.** Mine openings at the adit level (Bornhorst et al., 1986). Fault surfaces and slip lineations have been measured in the main adit and along the drift to the northeast.



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## **Sulfur isotopes as a record of differential contamination along the Cu-PGE mineralized Eastern Gabbro, Coldwell Complex, Canada**

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The Eastern Gabbro of the Coldwell Complex is a composite pluton that wraps around the eastern and northern margins of the complex and hosts a number orthomagmatic Ni–Cu–platinum group element (PGE) sulfide deposits (Good et al., 2015; 2019). The most well-characterized deposit is the Marathon conduit-type Cu–PGE deposit situated in the southern portion of the Eastern Gabbro. It, along with the other zones of mineralization, are largely hosted by the Two Duck Lake (TDL) gabbro, a coarse-pegmatitic gabbro that exhibits a subophitic texture. Three zones of mineralization occur in the Marathon deposit — the lower Footwall Zone, the Main Zone, and the upper W Horizon. The Footwall Zone is characterized by the highest Cu/Pd ratios that are within the range of mantle values, whereas the W Horizon is characterized by Cu/Pd values lower than mantle (Brzozowski et al., 2020). Base-metal sulfides (BMS) range from semi-massive to disseminated, and largely comprise variable amounts of pyrrhotite, chalcopyrite, and lesser pentlandite; the W Horizon is unique in that it contains significant bornite, limited pyrrhotite, and low sulfide content. Several zones of mineralization occur north of the Marathon deposit; from south to north these are the Four Dams and Boyer prospect, the Sally deposit, and the Redstone prospect (Good et al., 2017). Mineralization here is characterized by elevated Cu/Pd ratios and comprises a BMS assemblage similar to the Footwall and Main zones at Marathon, but with notably higher abundances of cubanite (Brzozowski et al., 2020).

In the Marathon deposit, the sulfide liquid was carried upwards to the site of emplacement from a sulfide pool located at depth, which formed by the addition of externally derived S from Archean sedimentary rocks. This Archean contamination is evident in the multiple S isotope composition of BMS in the Footwall and Main zones, namely a negative correlation between  $\delta^{33}\text{S}$ – $\delta^{36}\text{S}$  and non-zero  $\Delta^{33}\text{S}$ , which is characteristic of Archean S reservoirs (Shahabi Far et al., 2018). Similarly, the S/Se ratio of BMS in the Footwall Zone are elevated compared to mantle values, indicative of the addition of external S to the mineralizing system (Brzozowski et al., 2020).

In contrast to the Marathon deposit, BMS in the northern zones of mineralization are characterized by S/Se ratios that are largely lower than mantle ranges, indicating either i) contamination of these mineralized zones by a low S/Se source or ii) S loss. To attempt to address this ambiguity, the S isotope ( $\delta^{34}\text{S}$ ) composition of BMS at Four Dams, Boyer, Sally, and Redstone were characterized. In all of these zones of mineralization, BMS are characterized by  $\delta^{34}\text{S}$  values within the range of mantle values (Four Dams = 0.2 to 2.3, Boyer = 0.3 to 2.6, Sally = -0.7 to 2.5, Redstone = -0.1 to 2.6; Fig. 1). Considering the propensity of Ni–Cu–PGE systems to record evidence of external S addition, and the general inefficiency of other saturation mechanisms (e.g., decreasing  $f\text{O}_2$ , magma mixing; Ripley and Li, 2013) to generate economic sulfide deposits, the lack of  $\delta^{34}\text{S}$  signature could be the result of either i) dilution/destruction of the isotopic signature by interaction of the contaminated sulfide liquid with uncontaminated silicate melt (i.e., R factor), or ii) contamination by an Archean S source characterized by  $\delta^{34}\text{S} \sim 0\text{‰}$ . To assess the effect of R factor on the S isotope composition of BMS,  $\delta^{34}\text{S}$  is compared to bulk-rock Cu/Pd (i.e., a proxy for R factor). Although the Cu/Pd values of these mineralized zones varies over more than two orders of magnitude (525–909,000; Fig. 1), no systematic change is evident in the  $\delta^{34}\text{S}$  composition of BMS, suggesting that dilution of the contaminant signature may not be the cause

of the mantle-like values, but rather that the contaminant contained S that was processed through the Archean atmosphere. Given the current dataset, however, it is not possible to robustly assess the role of Archean contamination in the S saturation history of the northern mineralized zones in the Eastern Gabbro. This preliminary study, therefore, serves as the foundation for a future study characterizing the multiple S isotope composition of these mineralized zones and development of an augmented mineral deposit model.

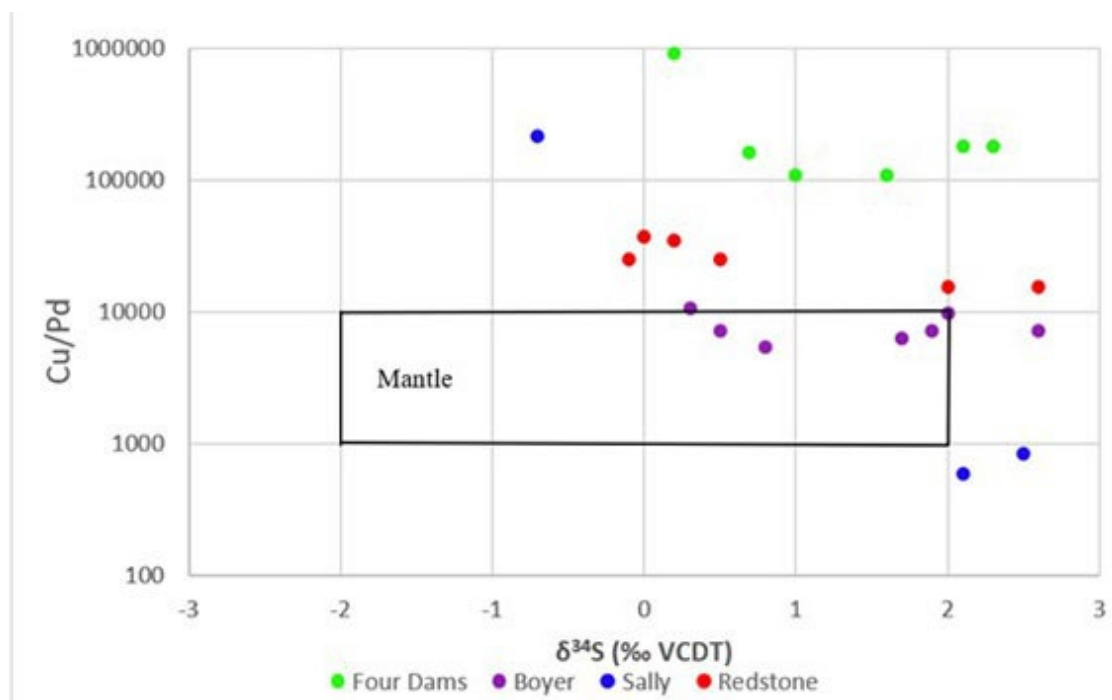


**Fig. 1.** Cu/Pd vs  $\delta^{34}\text{S}$  for the four northern mineralized zones. Black box indicates mantle ranges; Cu/Pd (1,000-10,000),  $\delta^{34}\text{S}$  ( $0 \pm 2\text{‰}$ ).

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## **Lithostratigraphy, mineralization, and petrogenesis of the MCR-related Sunday Lake Intrusion, NW Ontario**

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The Sunday Lake Intrusion (SLI), situated ~ 30 km north of Thunder Bay, Ontario, is a small, funnel-shaped, well differentiated ultramafic-mafic layered intrusion emplaced into Archean metasedimentary rocks during the early magmatic stage of the 1.1 Ga Midcontinent Rift. Although buried up to 400 meters below surface, it generates a 1.5 x 3km oval-shaped aeromagnetic and gravity anomalies centered over Sunday Lake. Beginning in 2008, exploration drilling of the Sunday Lake anomaly identified a well differentiated ultramafic-mafic intrusion containing several intervals of significant base and precious metal mineralization. Impala Canada (formerly North American Palladium) acquired the property in 2017 and has continued to conduct active exploration drilling. Building on earlier work of Flank, (2017), this talk reports on the lithostratigraphy, mineralization, and petrogenesis of the SLI based on petrographic studies of 37 samples and geochemistry from two drill core that completely profile the intrusion.

Petrographic and geochemical data from the two drill core show that the SLI can be subdivided into four main lithostratigraphic zones based largely on their cumulus mineralogy. Upsection, the main subdivisions are 1) a non-cumulate and well-mineralized Basal Mineralized Zone (BMZ), 2) a Lower Ultramafic Zone (LUZ) composed of Ol cumulates, 3) an Upper Ultramafic Zone (UUZ) dominated by Ol+Cpx cumulates, and 4) a Gabbro Zone (GZ) composed of Pl+Cpx+Ox+Ap cumulates grading upward to granophyre-enriched monzogabbro.

In addition to the significant contact-style Cu, Ni and PGE sulfide mineralization occurring in the Basal Mineralized Zone, several other mineralized intervals occur in the SLI. The most distinctive is Cu-PGE reef-style mineralization that occurs over an 80-130 meter interval straddling the contact between the UUZ and the GZ in both drill core. As is commonly observed in other orthomagmatic reefs generated by fractional crystallization-induced sulfide saturation (e.g., Skaergaard, Sonju Lake), PGE and Cu peaks are offset. Other narrow (<8m) intervals of elevated Cu-Ni-PGE concentrations occur in the UUZ.

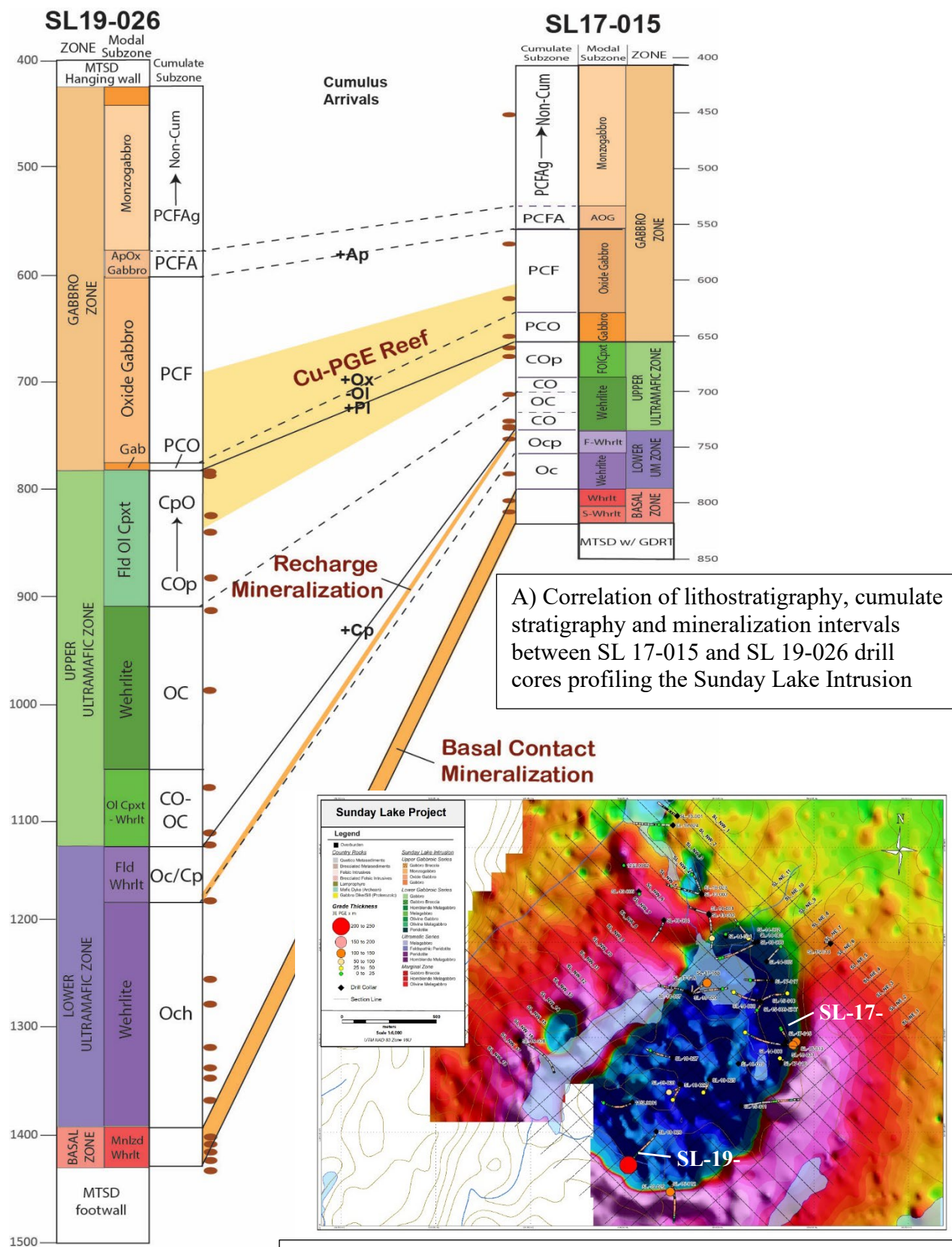
The stratigraphic sequence of cumulus mineral arrivals in the Sunday Lake intrusion is:

$\text{Ol}(\text{+CrSp}) \rightarrow \text{Ol+Cpx} \rightarrow \text{Pl+Cpx+Ol} \rightarrow \text{Pl+Cpx+Ox} \rightarrow \text{Pl+Cpx+Ox+Ap} (\text{+Gp}).$

Such a crystallization sequence is common among the mineralized early ultramafic-mafic intrusions of the Midcontinent Rift (e.g., Eagle, Tamarack, Seagull) and implies crystallization from a high-Mg, low-Al tholeiitic magma. This unidirectional progression of cumulus minerals and generally smooth chemostratigraphic trends of increasing IE abundance and decreasing mg#, suggest that the SLI formed by bottom-up fractional crystallization driving magmatic differentiation in a largely closed system. However, there are indications, based on abrupt increase in mg#, Cu and PGE and lithologic complexities, that the SLI was open to one or more recharge events during formation of the LUZ and UUZ.

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B) Location of drill holes SL-17-015 and SL-19-026 relative to the aeromagnetic anomaly associated with the Sunday Lake Intrusion.

## U-Pb zircon ages and Lu-Hf isotopes from Precambrian basement along the Trans-Hudson Foldbelt/Superior Craton Boundary Zone, central North Dakota

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Two Precambrian basement cores were recently cut from Oliver County of central North Dakota, along the proposed Trans-Hudson foldbelt and Superior craton boundary zone (Fig. 1) (Klasner and King, 1986; Sims et al., 1991). Intersecting basement at 2969.7 m (9,743 ft) and 3132.9 m (10,278.5 ft) depths respectively, the J-ROC1 1 and J-LOC 1 cores offer new opportunities to evaluate this region's buried crystalline basement and to determine potential affinity with the ~1.6-1.8 Ga Trans-Hudson foldbelt and/or ~2.7 Ga Superior craton.

The cores were logged and representative samples were analyzed at Washington State University for major and trace elements, REEs, U-Pb zircon age dates, and Hf zircon analyses.

The top two meters of J-ROC1 1 is composed of heavily weathered amphibolite or granitic gneiss intruded by an approximately 10 cm wide granitic dike. Unweathered foliated amphibolite dominates the lithology to 2976.5 m (9765.5 ft), which is composed of hornblende, plagioclase, and biotite. Granitic dikes varying from 2 - 3 cm to 14 cm in width occur sporadically.

The J-LOC 1 core is primarily foliated hornblende-plagioclase-biotite amphibolite of varying fine to coarse grain size. Accessory minerals include opaque minerals (magnetite and pyrite), zircon, and apatite. It contains thin pygmatic quartz veins, calcite veins, high angle altered fractures, and intrusions of medium grained to pegmatitic granite which range from a few cm to 60 cm in width. The unweathered granitic samples have characteristic SiO<sub>2</sub> values (71.7-73.3 wt.%), and normalized REE ratios (La/Lu)<sub>N</sub> of 78-80. Amphibolite samples range widely in SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, and trace element contents.

The J-ROC1 1 foliated amphibolite/granitic gneiss samples (37672-1 and 37672-3) yielded ~2.68 Ga Archean zircons while the intrusive granite sample (37672-2) contained zircons of both Archean and younger, Paleoproterozoic 1.78 Ga ages. The foliated amphibolite of J-LOC 1 (37380-2) contained 1.83 Ga zircons while the intrusive granitic samples yielded either slightly younger Paleoproterozoic ages of 1.75 Ga (37380-4), or mixed Paleoproterozoic-Archean zircons (37380-1 and 37380-3).

The two J-ROC1 1 Archean samples (37672-1 and 37672-3) and the Archean component of 37672-2 have positive initial epsilon Hf values spanning a narrow isotopic range ( $\epsilon\text{Hf}(i) = +3.6 \pm 1.3$ ,  $+3.7 \pm 1.9$ , and  $+4.1 \pm 1.7$ ) indicating derivations from a relatively homogeneous depleted mantle at their crystallization age. There is no evidence of older (pre-2.68 Ga) crust in their genesis. The Paleoproterozoic samples of the J-LOC 1, on the other hand, represent either a depleted mantle component (e.g., 37380-2,  $\epsilon\text{Hf}(i) = +6.6 \pm 1.1$ ) or a mixture of depleted mantle and older (Neoproterozoic) crustal components (e.g., 37380-4,  $\epsilon\text{Hf}(i) = +2.2 \pm 4.3$ ; 37380-1,  $\epsilon\text{Hf}(i) = -1.7 \pm 3.0$ ) consistent with the existence of mixed ~2.68 Ga and ~1.78 Ga components present in these samples.

The basement at J-ROC1 1 appears to be Archean foliated amphibolite/granitic gneiss intruded by Paleoproterozoic granitoids, while that at J-LOC1 1 consists of Paleoproterozoic foliated amphibolite intruded by slightly younger Paleoproterozoic granitoids. All intrusive

Paleoproterozoic granitoids appear to comprise a mixture of depleted mantle and older (Archean) crustal components. Overall, both cores contain a mix of Paleoproterozoic and Archean crustal components, consistent with the regional interpretation that both cores are from the Superior/Trans-Hudson boundary zone (Klasner and King, 1986; Sims et al., 1991).

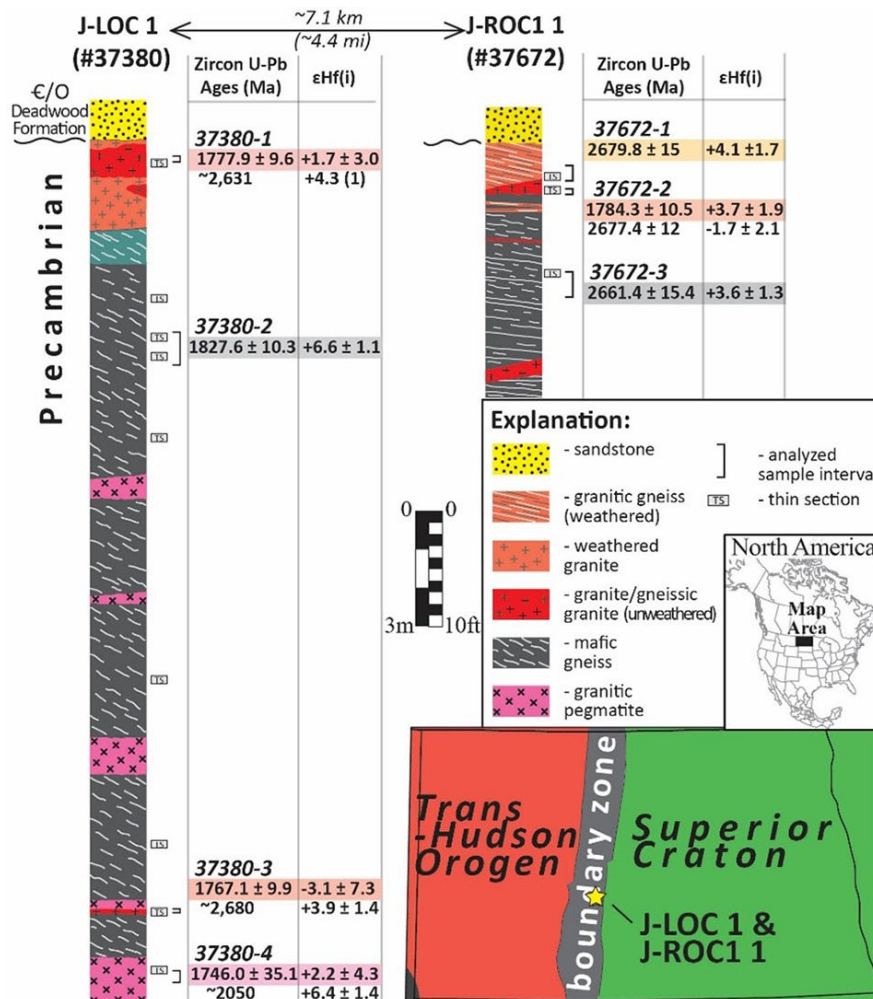


**Figure 1:** Core lithology illustrations with U-Pb and εHf data from analyzed samples. NDIC (North Dakota Industrial Commission File No: 37380 = J LOC 1, and 37672 = J ROC1 1). Regional geologic basement map modified from Sims et al. (1991).

**Acknowledgments:** We appreciate funding by the North Dakota Geological Survey.

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## Bringing the Wyoming Province and its orogenic gold potential home to the Superior Province, a look into the South Pass greenstone belt and its Abitibi gold links

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The Wyoming Province is a ~500,000 km<sup>2</sup> Archean craton that encompasses basement rocks beneath most of Wyoming and portions of adjacent states. These Archean basement rocks are exposed as windows through Phanerozoic rocks in the cores of Laramide (Paleocene) uplifts but represent <10% of the total exposed area of the Wyoming craton (Houston et al. 1993). These basement rocks are composed of scarce Paleoarchean to Mesoarchean gneisses, localized Mesoarchean to Neoarchean supracrustal rocks and voluminous Neoarchean granitic plutons and gneisses (Frost and Frost 1993). Numerous publications over the last 30 years have shown ample evidence that the Wyoming Province represents a rifted, transported, and rotated remnant of the southern Superior Province (Frost and Frost, 1993; Grace et al., 2006 and references therein). Such evidence can be used to interpret the mineral potential of rock sequences of the Wyoming Province and herein we present data on orogenic gold mineralization within the greywacke-slate dominated Archean supracrustal rocks of the South Pass greenstone belt (Figure 1).

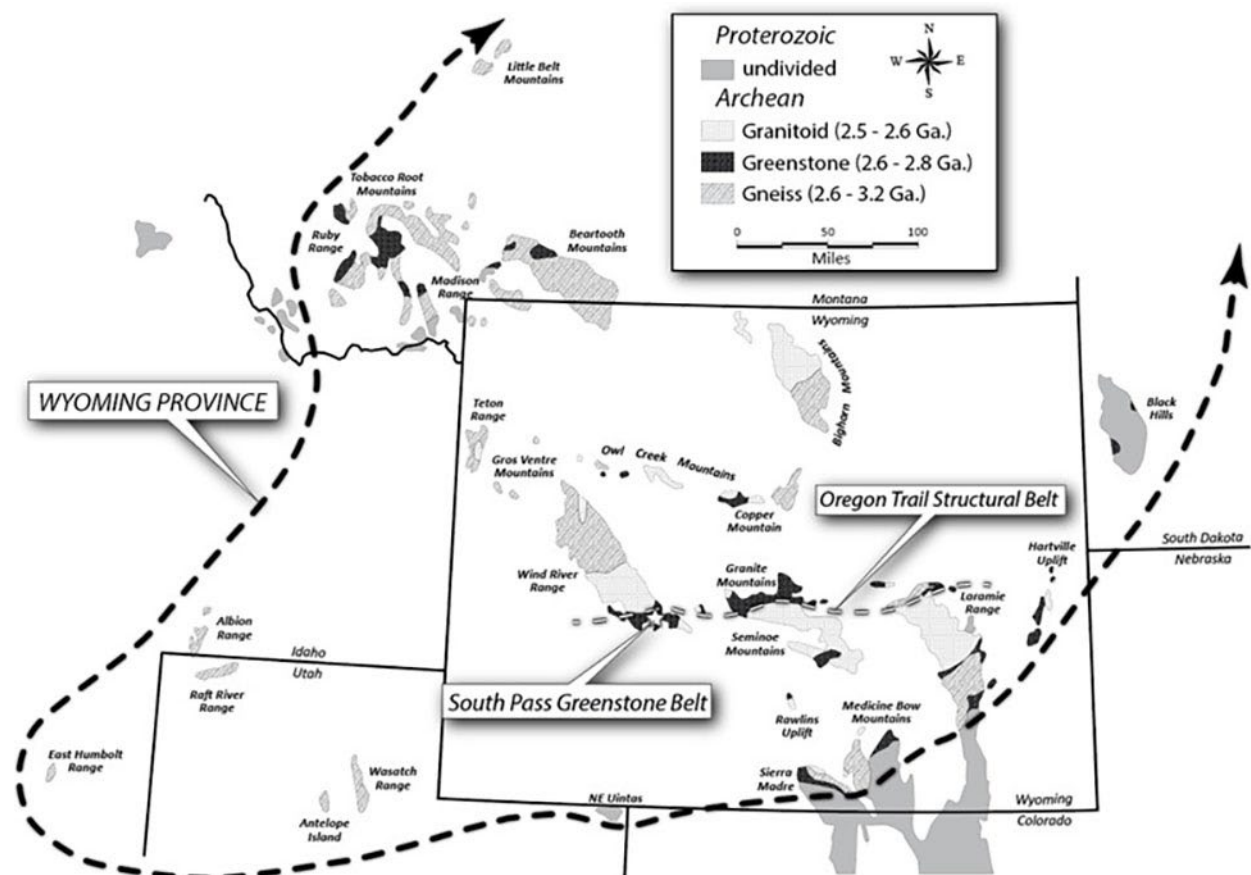


**Figure 1.** Sketch map of the Wyoming Province, showing the location of the South Pass greenstone belt as well as the Laramide uplift exposures of Precambrian age terranes. Modified after Hausel (1991).

The South Pass Greenstone Belt, which lies near the southeastern tip of the Wind River Mountain Range, is one of several fragmented, metamorphosed, volcanic-sedimentary Archean supracrustal terranes exposed in the cores of Laramide uplifts of the Wyoming Province. Accounts of past producing gold properties in the South Pass Greenstone Belt (Bow, 1986; Hausel, 1991) document mining on a small scale, at narrow widths, and largely confined to oxidized ores above the water table (<80 feet) associated with shear zones. Available data suggests that much of the strike length of a given shear-hosted vein system is anomalous in gold with localized steeply plunging high-grade ore shoots systematically occurring parallel to the trend and plunge of stretching lineations within shear zones.

Big Rock Exploration's (BRE) recent work in the South Pass greenstone belt confirms the observations of Bow (1986) and Hausel (1991) who showed that gold mineralization is associated with shear zone hosted quartz veins and vein arrays in subsidiary shear zones associated with the Oregon Trail Structural Belt. As well, gold mineralization generally correlates with biotite and sulfide content (pyrrhotite>pyrite>arsenopyrite), and the shear hosted quartz veins typically display 3-10 meter-wide alteration envelopes of bleached, sericitized and/or silicified greywacke. The next step for BRE is to apply the geospatial concepts developed (namely that orogenic gold deposits are largely hosted in rocks proximal to late Riedel P-shears) by Peterson (2001) on the Timmins, Kirkland Lake, and Hemlo gold camps of the Abitibi-Wawa greenstone terrane (Figure 1) via detailed geological/structural mapping and drilling

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## **Mineralogy and Petrology of the Good Hope Carbonatite Complex, Marathon, ON**

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The Good Hope carbonatite is located northwest of Marathon, Ontario (49° 02' N, 86° 43' W), emplaced within the Archean gneisses of the Wawa Subprovince (Figure 1). It occurs along the northwest margin of the Prairie Lake complex that has a U-Pb age of 1160 Ma (Wu et al., 2017). Due to extensive glacial overburden, the Good Hope carbonatite has very limited outcrop. Most thin sections examined were cut from drill core for optical petrography, scanning electron microscopy and backscattered electron imagery and quantitative EDS. The objectives of this research are to characterize the carbonate and other mineralogy of the Good Hope carbonatite, use mineral compositions and textural associations to discuss the petrogenesis, and to compare and contrast the mineralogy of the Good Hope and Prairie Lake carbonatite to assess potential relationships.

The major rock forming minerals in the Good Hope carbonatite are ferroan dolomite, calcite, and apatite. The apatite occurs predominantly as elongated apatite clasts that define heterogeneous banding within the carbonatite. The groundmass is composed of either ferroan dolomite or calcite with significant variation in the modal mineralogy at the thin section scale. The minor minerals include dolomite, K-feldspar, quartz, chlorite, magnetite, barite, biotite – phlogopite, magnesio-arfvedsonite, aegirine, pyrochlore, albite, and fluorite. The accessory minerals include pyrite, synchysite-(Ce), rutile, siderite, strontianite, thorite, parisite-(Ce), bastnaesite-(Ce), burbankite, and zircon. Syenite clasts, on the scale of centimeters to tens of centimeters in size are incorporated as xenoliths and disaggregated xenoliths that commonly exhibit a reaction rind of biotite – phlogopite ± magnesio-arfvedsonite in contact with the carbonatite.

The apatite occurs as euhedral-to-subhedral, very fine-to-medium-, randomly oriented grains. The pyrochlore are almost exclusively associated with the apatite clasts and are variably altered to columbite or fersmite (Figure 2). Apatite is typically the first phase to crystallize from a carbonatitic magma (Mitchell et al., 2017) and the close association with pyrochlore suggests they accumulated together and were redistributed by a later pulse of magma. The ferroan dolomite and calcite are typically anhedral, ranging from 100 – 6000 µm in size with variation occurring on a millimeter- to-centimeter-scale. The calcite and ferroan dolomite variably contain inclusions of REE-fluorocarbonates, burbankite, strontianite, barite, quartz, magnetite, and fluorite. The presence of burbankite inclusions in ferroan dolomite and calcite supports it being a primary magmatic phase (Chakhmouradian and Dahlgren, 2021). In addition to occurring as inclusions, the REE-fluorocarbonates also occur as fine-grained syntaxial intergrowths or medium grains of synchysite-(Ce) with parisite-(Ce) and/or bastnaesite-(Ce) lamellae, intergrown with thorite or strontianite. Veins and veinlets of quartz, fluorite, chlorite, calcite, and ferroan dolomite that crosscut the groundmass and the apatite clasts provide evidence for late-stage hydrothermal processes.

This sequence of emplacement: syenite; magmatic apatite + pyrochlore; magmatic calcite- and ferroan dolomite-carbonatite; magmatic-hydrothermal ferroan dolomite; late-stage hydrothermal calcite + quartz + chlorite + fluorite +REE-fluorocarbonates is similar to observations at other alkaline rock – carbonatite complexes (e.g. Fen Complex, Marien et al., 2018). Given that the Prairie Lake complex consists of silicate-rich rocks and contains only calcite carbonatites, it is possible that the Good Hope intrusion could be the continuation of this system.

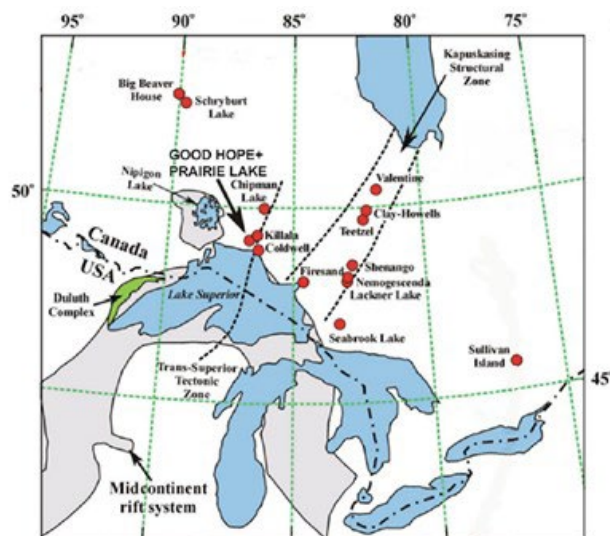


**Figure 1:** Location of alkaline rock – carbonatite complexes in Ontario showing the spatial relationship of Good Hope to the Midcontinent rift system and the Trans-Superior Tectonic Zone (Mitchell et al., 2020).

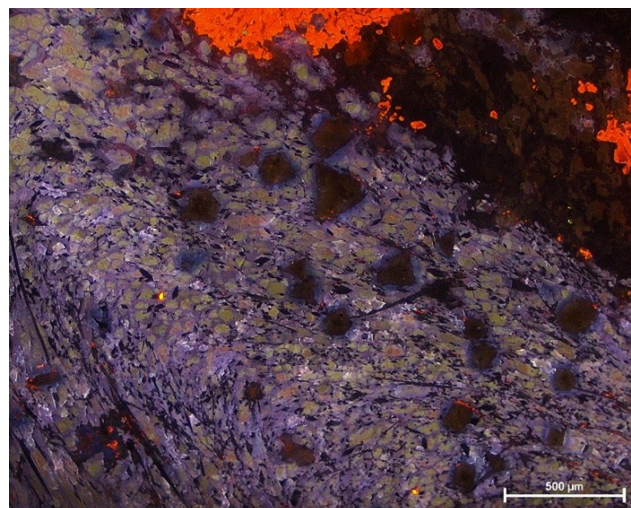


**Figure 2:** Cathodoluminescence image of pyrochlore within an apatite clast that has acicular magnesio-arfvedsonite defining a fold.

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## **Magma Recharge and the distribution of Copper and Nickel in the Keweenaw Large Igneous Province**

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The Keweenaw large igneous province (LIP) was formed over a protracted period of magmatism that emplaced Cu-Ni-PGE bearing mafic to ultramafic intrusions along the arcuate Mid-Continent Rift system, thus creating one of the largest critical mineral resources in North America. The magmatic activity associated with the Keweenaw LIP has been divided into a series of tectonomagmatic stages extending from at least 1115 Ma to 1080 Ma. Of the six stages of formation, significant orthomagmatic sulfide deposits were formed during Stage 1 (plume impact stage; 1115-1110 Ma), Stage 2 (early stage; 1110-1105 Ma), and the Stage 4 (the main stage; 1101-1094 Ma). Stage 1 and 2 intrusions in the Minnesota and Michigan are Ni-rich while those of stage 4 in the Duluth Complex are considerably more copper-rich. Here we discuss a potential mechanism of copper enrichment via magma recharge-evacuation-fractional crystallization (RE AFC) where the parameters of differentiation are based upon a conceptual model for the formation of continental LIPs.

It has been recognized that continental LIPs form in a series of phases that reflect the conditions of magma generation and differentiation prior to the eruption and eventual formation of continental flood basalts (Jerram and Widdowson, 2005). Early phases of LIP formation are dominated by more primitive lavas, that pass through a magma plumbing system that is immature and inefficient at differentiating magmas (Steiner et al, 2021). However, the magmatic plumbing system of the most voluminous eruptive phase is mature and capable of differentiating magmas to a considerable degree. The key difference between these two periods is the amount of magma recharge, which has a profound impact on the geochemical composition of the resultant magmas where compatible elements become buffered and incompatible elements become enriched (Lee, Lee and Wu, 2014).

The relative Cu-enrichment of mineralized Stage 4 intrusions compared to earlier Ni-rich Stage 1 and 2 intrusions may be explained by several mechanisms. Mechanisms such as sulfide upgrading and high-R factors have been recognized as important contributors to Cu-rich mineralization (Peterson and Boerst, 2013). However, recent chemo-stratigraphic examinations of Keweenaw LIP lavas from the Keweenaw Peninsula have demonstrated that RE AFC processes are controlling erupted lava compositions during the eruption of Stage 4 lavas (Davis et al., 2021). To test the effect of RE AFC on the proportions of Ni and Cu that may be available to form an orthomagmatic sulfide deposit, RE AFC geochemical modelling utilizing the equations of Lee et al. (2014) were performed on a generalized basaltic composition (MgO = 10%, Ni = 250 ppm, Cu = 116 ppm (Prinz, 1967)). Figure 1 demonstrates the liquid line of descent for Cu, Ni, and MgO during RE AFC differentiation and pure fractional crystallization. During pure fractional crystallization, MgO and Ni behave compatibly, gradually decreasing in concentration with continued differentiation while Cu gradually increases. However, during RE AFC differentiation, both Ni and MgO become buffered while Cu becomes decoupled, increasing in concentration while Ni and MgO remain the constant. The consequence of this decoupling is that Cu can become considerably enriched relative to Ni, thereby producing a magma that contains greater than anticipated Cu concentrations compared to pure fractional crystallization. When this Cu-enriched magma reaches sulfur saturation, the subsequent sulfide magma would have a greater abundance of Cu to scavenge, resulting in the Cu-rich sulfide deposits observed in the Duluth Complex.

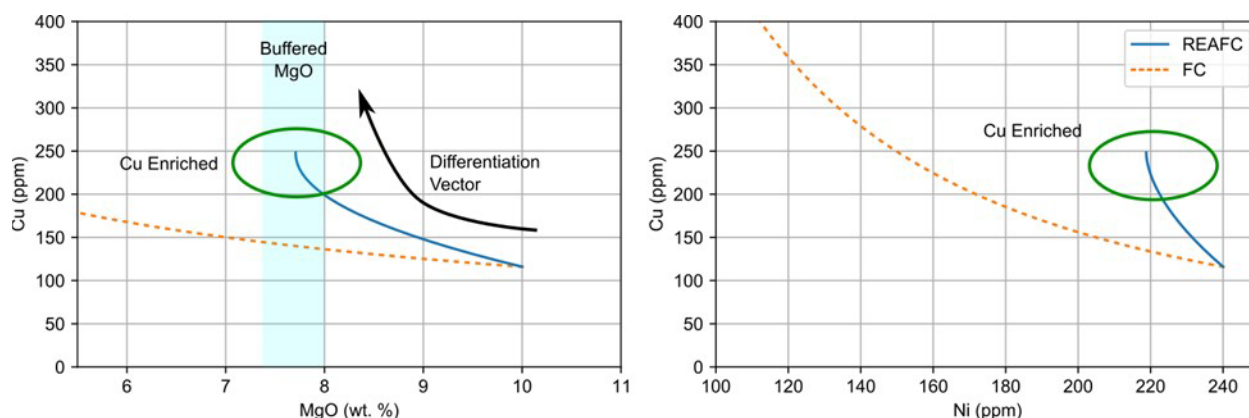


**Figure 1.** REAFC calculations (Lee, Lee and Wu, 2014) for a generic basalt. Model parameters are recharge/evacuation = 0.43, assimilation = 0.07, fractional crystallization = 0.5. Crystallizing phases were olivine (25%), plagioclase (65%) and clinopyroxene (15%).

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## **Episodic activation of magma conduits at the Midcontinent Rift System: Evidence from the Eagle system of intrusions in the Upper Peninsula of Michigan**

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Magmatism at the Midcontinent Rift System has been classified into three main stages: Plateau stage: 1108 – 1105 Ma, Rift stage: 1102 – 1083 Ma and Late-rift stage: 1083 – 1060 Ma (Woodruff et al., 2020). The funnel-shaped Eagle mafic-ultramafic intrusion, located in the Upper Peninsula of Michigan has been dated at  $1107.2 \pm 5.7$  Ma, using U-Pb baddeleyite studies on samples of feldspathic peridotite (Ding et al., 2010). The Eagle East intrusion is located about 500 meters to the East of Eagle intrusion, and it is similar to the Eagle intrusion in composition and mode of occurrence. New exploration studies have revealed a near-vertical plug-like gabbroic intrusive body at the bottom of the Eagle East ultramafic intrusion (Figure 1). U-Pb baddeleyite analysis on this gabbro yielded an age of  $1103.4 \pm 1.2$  Ma.

From the observed mode of occurrence and the timing of crystallization, it can be inferred that this Late Eagle East gabbroic intrusion was emplaced along the same magma conduit as the Eagle East intrusion but at a much later time. The distinct petrological and geochemical characteristics of the late gabbroic intrusion provides evidence that a much differentiated, SiO<sub>2</sub>-rich, and MgO-poor magma was responsible for its crystallization when compared to the parental magma of the Eagle East and the Eagle intrusions.

From the above two lines of evidence, it can be argued that the Eagle East intrusion and the Late Eagle East gabbroic intrusion were crystallized from separate pulses of magma released from a staging magma chamber in the lower crust or upper mantle. However, the younger gabbroic intrusion was crystallized from a more differentiated magma. After the separation of early batches of magma which formed the Eagle and Eagle East peridotitic intrusions, continued differentiation of the residual liquid in staging reservoirs formed the magma that was responsible for the Late Eagle East gabbroic intrusion.

The Eagle and Eagle East peridotitic intrusions represent MgO-rich and Al<sub>2</sub>O<sub>3</sub>-poor magmatic pulses comparable to the Lower Siemen's Creek Volcanics (Nicholson et al., 1997). These magmas ascended from deep staging chambers during the Plateau Stage of magmatism in the Midcontinent Rift. However, the younger gabbroic intrusion that was emplaced along the magmatic conduit the Eagle East intrusion is composed of ~7 wt.% MgO and ~14 wt.% of Al<sub>2</sub>O<sub>3</sub>. This is in strong contrast to >18 wt.% MgO and <9 wt.% of Al<sub>2</sub>O<sub>3</sub> in the peridotite and melatroctolite units of the Eagle and Eagle East intrusions above. This implies that the conduits responsible for magmatic ascent during the Plateau Stage of the Midcontinent Rift were reactivated during small-scale magmatic events shortly after the Plateau Stage. These magmatic upheavals could be regarded as transitional to the voluminous basaltic magmatism in the Lake Superior Region during the Rift Stage of the Midcontinent Rift System.

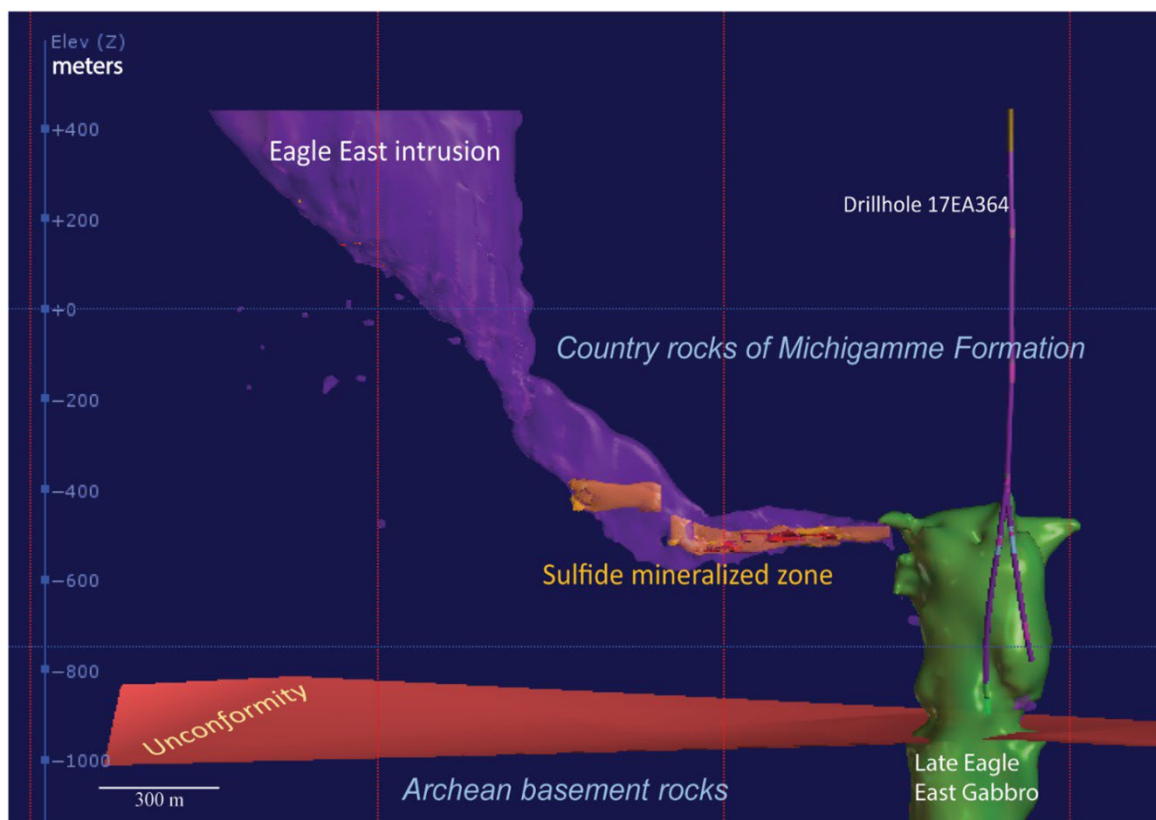


**Figure. 1.** North-looking 3D view of the funnel-shaped Eagle East peridotitic intrusion and the younger Gabbroic intrusion at the bottom.

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### 3-D upper crustal architecture of the East range of the Sudbury basin – a Metal Earth collaborative research project with Vale & Glencore

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#### Introduction

The Sudbury structure is attributed to a large comet impact that occurred at around ~1.85 Ga (Krogh et al., 1984; Petrus et al., 2015). The structure comprises the 58 by 28 km elliptical Sudbury Igneous Complex (SIC) that has undergone multi-phase deformation during NW-SE crustal shortening of an original circular shape (Lightfoot, 2016). The structure overlies Archean age granitic, gneissic and granulitic basement rocks (Krogh et al., 1984) in the North and East ranges, whereas in the south range it overlies Paleo-Proterozoic age metasedimentary and metavolcanic rocks. This structure is known for world class Ni-Cu-Co-PGE-Au deposits and thus has significant economic impact on Sudbury region and Canada. In the East range of the Sudbury structure, fewer economically viable deposits have been found to date. To aid in the search of new deposits or targets, a research initiative was undertaken as part of an ongoing Metal Earth NSERC-CRD project in collaboration with Vale & Glencore.

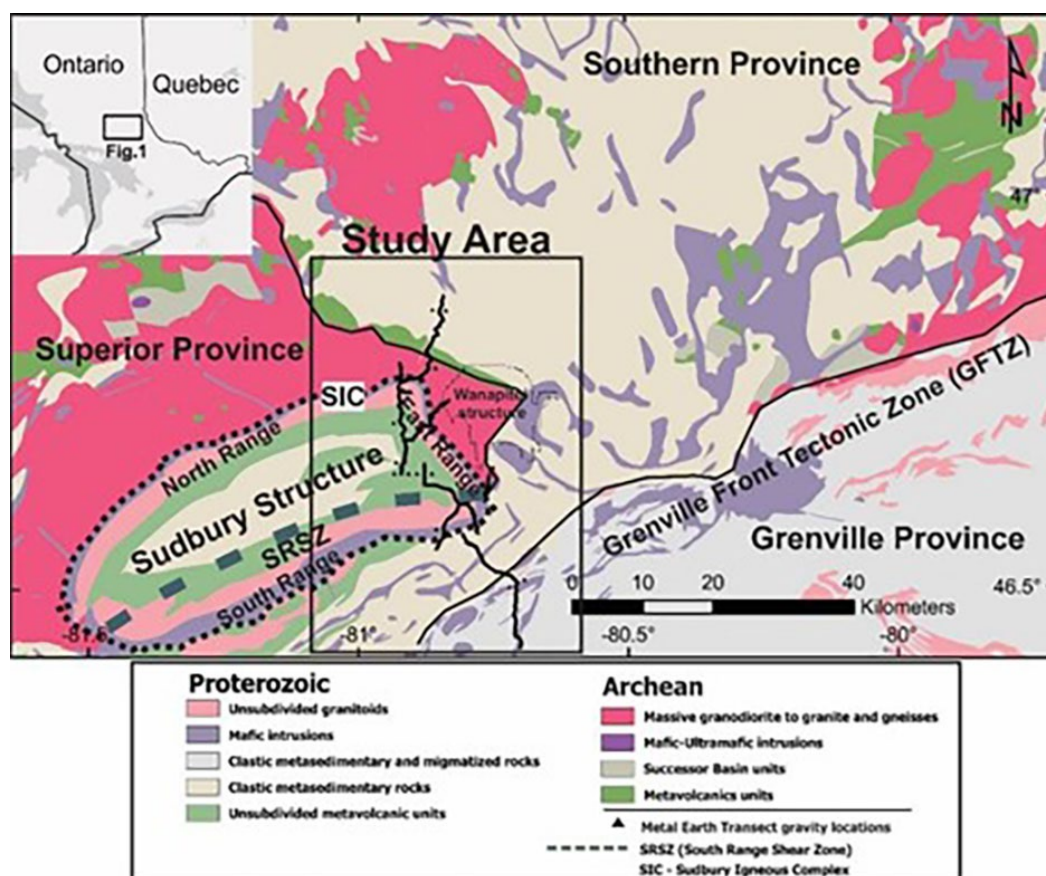


**Figure 1:** Study area in the eastern part of the Sudbury impact structure, overlain on the simplified geological map (Montsion et al., 2018).

## **Methodology**

In the summers of 2017 and 2018, multiple geophysical datasets (regional and high resolution seismic, broadband (BBMT) and audio-frequency magneto-telluric (AMT) and ground based gravity data) were collected in the East range of the Sudbury basin. In addition, Vale provided borehole-constrained interfaces of a 3-D geological model and final processed seismic sections processed by Hi-Seis. The regional aeromagnetic, gravity and Mineral deposit inventory data utilized are from public domain sources. The main aim of this research is to study the shallow to deep crustal-scale controls on metal endowment and identify potential zones of mineralisation. We carried out three-dimensional inversions on potential field and electromagnetic datasets and integrated the final models with other geophysical and geological datasets for comprehensive subsurface interpretation.

## **Conclusions**

We have observed a good correlation between various geophysical models and geological datasets and identified three shallow zones of anomalous conductivity in the AMT model: 1) in the north-east range proximal to the basal contact of the SIC with basement rocks, 2) in the east-central area corresponding to Whitewater Group sediments in the upper stratigraphy of the Sudbury basin and 3) in the south-east range, also proximal to the basal-contact of the SIC. The deeper-looking BBMT model also delineated mid to deep crustal conductors that may be conduits connected to the shallow conductors observed in the AMT model. The potential-field inversions provide geophysical evidence of folding and/or faulting of mafic/ultramafic rocks in the Archean basement and suggests that this deformation may have resulted in alteration and weaker magnetic and gravity fields in the East Range of the Sudbury impact structure. High-resolution seismic images also support this deep-seated faulting. We suggest that deep-seated faults could have acted as conduits for hydrothermal fluid flow from deep crustal conductors to shallow conductors thus enhancing the locus of mineralization in the SIC footwall.

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## **Geochemical and isotopic composition of Midcontinent Rift-related intrusions of the Thunder Bay North Igneous Complex, northwestern Ontario, Canada**

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The Thunder Bay North Igneous Complex (TBNIC) is located approximately 50 km northeast of Thunder Bay, Ontario, Canada. It comprises two Cu–Ni–PGE-mineralized mafic–ultramafic intrusions, the Escape Intrusion (EI) and the Current Intrusion (CI), and five smaller mafic–ultramafic intrusions whose mineralization potential has yet to be fully assessed. These are called the Lone Island Lake (LI), Greenwich (GI), Southeast Anomaly (SEA), and 025 intrusions, and the East–West Connector (EWC). This study focuses on these smaller, poorly characterized intrusions. These gabbroic to peridotitic intrusions, which are characterized by high magnetic anomalies, crosscut the Archean granitoids and metasedimentary rocks of the Quetico Subprovince (Fig. 1). Petrographic, geochemical, and isotopic characterisation of these intrusions will add to our knowledge of magmatism related to the Midcontinent Rift System (MRS) and provide a better understanding of the conditions that produced the Cu–Ni–PGE-mineralized CI and EI intrusions. Petrographic analysis of the five intrusions indicates that they are gabbroic to peridotitic in composition and contain up to 6–9% sulfide. The sulfides predominantly comprise pyrite, with lesser amounts of chalcopyrite and pyrrhotite.

The five intrusions are characterized by high incompatible element contents, light rare-earth element (LREE) enrichment, with La/Sm<sub>n</sub> of 2–3.7, variable heavy REE (HREE), with Gd/Yb<sub>n</sub> of 1–6, and similar Th/Nb<sub>n</sub> of 0.09–0.11. These REE characteristics are similar to other MRS-related intrusions and plume-derived ocean island basalt (Hollings et al., 2007). A range of primitive mantle-normalized spider diagrams have been identified, with two main groups (Fig. 2a). One group comprises the LI, 025, SEA, and EWC; these intrusions are characterized by LREE enrichment and moderate HREE fractionation. The second group comprises the GI, which has less fractionated HREE. A notable Sc depletion is present in the spider diagrams for the LI, GI, SEA, and EWC intrusions; this may be the result of garnet retention in the mantle (Chassé et al., 2018), and/or clinopyroxene fractionation during magma transport and emplacement. Both patterns in spider diagrams exhibit a distinct positive V anomaly (Fig. 2a). Given the lack of positive Ti anomalies in these rocks, this is probably not the result of oxide accumulation, but rather could be the result of clinopyroxene accumulation.

Samarium–Nd and Rb–Sr isotopes have been measured to assess the role of crustal contamination in the formation of the intrusions. All of the intrusions are characterized by variably negative  $\epsilon_{\text{Nd}(1107.9\text{Ma})}$  values of -7.49 to +0.14 and Sr<sub>i</sub> of 0.70309 to 0.70587. The lowest two  $\epsilon_{\text{Nd}(1107.9\text{Ma})}$  values of -7.20 and -7.49 are from samples of the GI with the flatter trace-element patterns (Fig. 2a and 2b). The other intrusions exhibit variations in their  $\epsilon_{\text{Nd}(1107.9\text{Ma})}$  of 0.14 to -4.64. Two country rock samples (an Archean metasedimentary rock and a granitoid) have  $\epsilon_{\text{Nd}(1107.9\text{Ma})}$  values of -20.50 and -20.19, Sr<sub>i</sub> values of 0.763659 and 0.705729, and Th/Nb<sub>n</sub> of 2.33 and 1.50, respectively. The negative  $\epsilon_{\text{Nd}(1107.9\text{Ma})}$  values for the intrusions and the country rocks, along with their elevated bulk-rock Th/Nb<sub>n</sub> ratios, indicate that the intrusions were contaminated by old crustal material. Plotting  $\epsilon_{\text{Nd}(1107.9\text{Ma})}$  against Sr<sub>i</sub> shows isotopic similarity between EWC, LI, 025,

and SEA intrusions and part of the GI, whereas the GI samples with higher  $\text{Sr}_i$  and Lower  $\epsilon_{\text{Nd}}(1107.9 \text{ Ma})$  are distinct and likely reflect a greater degree of contamination (Fig. 2b).

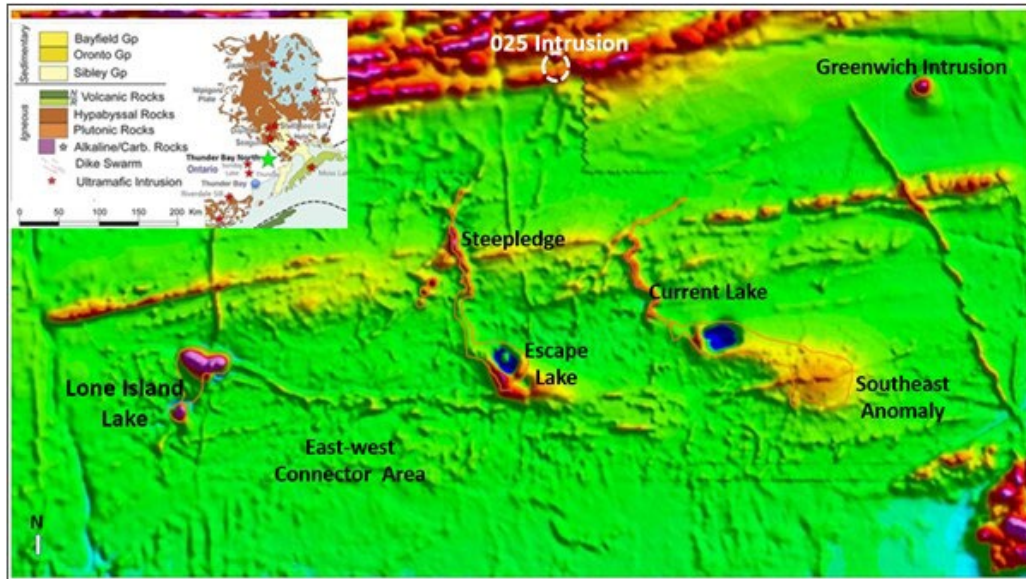


**Fig.1.** An aeromagnetic map showing the locations of (EI), (CI), (LI), (GI), (SEA), 025, and the (EWC) intrusions (Geoff Heggie and MacTavish, 2015).

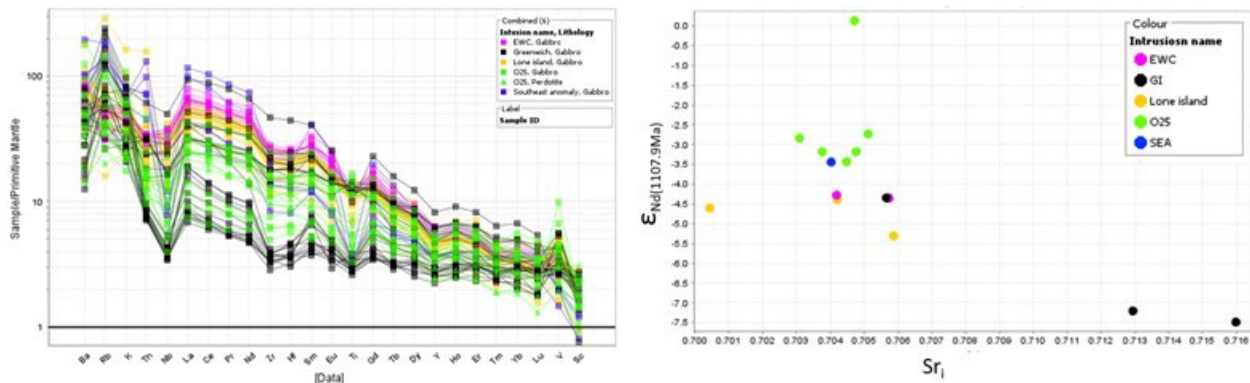


**Fig. 2. (a)** Primitive mantle normalized diagram for LIL, GI, SEA, 025, and EWC intrusions (Normalizing values of Sun and McDonough, 1989). **(b)**  $\epsilon_{\text{Nd}}(1107.9 \text{ Ma})$  vs  $\text{Sr}_i$  diagram showing the variation between the five intrusions.

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