ISSN 1916-6117 (online)
ISBN 978-1-4868-6589-5 (PDF)

ISSN 0826-9580 (print)
ISBN 978-1-4868-6588-8 (print)

THESE TERMS GOVERN YOUR USE OF THIS DOCUMENT

Your use of this Ontario Geological Survey document (the "Content") is governed by the terms set out on this page ("Terms of Use"). By downloading this Content, you (the "User") have accepted, and have agreed to be bound by, the Terms of Use.

Content: This Content is offered by the Province of Ontario's *Ministry of Mines* (MINES, or the Ministry) as a public service, on an "as-is" basis. Recommendations and statements of opinion expressed in the Content are those of the author or authors and are not to be construed as statement of government policy. You are solely responsible for your use of the Content. You should not rely on the Content for legal advice nor as authoritative in your particular circumstances. Users should verify the accuracy and applicability of any Content before acting on it. The Ministry does not guarantee, or make any warranty express or implied, that the Content is current, accurate, complete or reliable. The Ministry is not responsible for any damage however caused, which results, directly or indirectly, from your use of the Content. The Ministry assumes no legal liability or responsibility for the Content whatsoever.

Links to Other Web Sites: This Content may contain links, to Web sites that are not operated by MINES. Linked Web sites may not be available in French. The Ministry neither endorses nor assumes any responsibility for the safety, accuracy or availability of linked Web sites or the information contained on them. The linked Web sites, their operation and content are the responsibility of the person or entity for which they were created or maintained (the "Owner"). Both your use of a linked Web site, and your right to use or reproduce information or materials from a linked Web site, are subject to the terms of use governing that particular Web site. Any comments or inquiries regarding a linked Web site must be directed to its Owner.

Copyright: Canadian and international intellectual property laws protect the Content. Unless otherwise indicated, copyright is held by the King's Printer for Ontario.

It is recommended that reference to the Content be made in the following form:

Ontario Geological Survey 2022. Summary of Field Work and Other Activities, 2022; Ontario Geological Survey, Open File Report 6390, 308p.

or, for partial Content

Amyotte, E.G., Kurucz, S.V., Paju, G.F., Jonsson, J.R.B. and Kurcinka, C.E. 2022. Investigation of biogeochemical exploration techniques to aid in the exploration for lithium-cesium-tantalum pegmatite dikes: Project description and preliminary observations; *in* Summary of Field Work and Other Activities, 2022, Ontario Geological Survey, Open File Report 6390, p.31-1 to 31-7.

Use and Reproduction of Content: The Content may be used and reproduced only in accordance with applicable intellectual property laws. *Non-commercial* use of unsubstantial excerpts of the Content is permitted provided that appropriate credit is given and Crown copyright is acknowledged. Any substantial reproduction of the Content or any *commercial* use of all or part of the Content is prohibited without the prior written permission of MINES. Substantial reproduction includes the reproduction of any illustration or figure, such as, but not limited to graphs, charts and maps. Commercial use includes commercial distribution of the Content, the reproduction of multiple copies of the Content for any purpose whether or not commercial, use of the Content in commercial publications, and the creation of value-added products using the Content.

Contact:

FOR FURTHER INFORMATION ON	PLEASE CONTACT:	BY TELEPHONE:	BY E-MAIL:
The Reproduction of the EIP or Content	MINES Publication Services	Local: (705) 670-5691 Toll-Free: 1-888-415-9845, ext. 5691 (inside Canada, United States)	Pubsales.ndm@ontario.ca
The Purchase of MINES Publications	MINES Publication Sales	Local: (705) 670-5691 Toll-Free: 1-888-415-9845, ext. 5691 (inside Canada, United States)	Pubsales.ndm@ontario.ca
Crown Copyright	King's Printer	Local: (416) 326-2678 Toll-Free: 1-800-668-9938 (inside Canada, United States)	Copyright@ontario.ca

Ontario

Ontario Geological Survey
Open File Report 6390

Summary of Field Work and Other Activities, 2022

2022

Ontario

ONTARIO GEOLOGICAL SURVEY

Open File Report 6390

Summary of Field Work and Other Activities, 2022

by

Ontario Geological Survey

Edited by R.M. Easton, S. Préfontaine, M. Duguet, O.M. Burnham, R.P.M. Mulligan, C. Béland Otis, F.R. Brunton and C. Gao

2022

Parts of this publication may be quoted if credit is given. It is recommended that reference to this publication be made in the following form:

Amyotte, E.G., Kurucz, S.V., Paju, G.F., Jonsson, J.R.B. and Kurcinka, C.E. 2022. Investigation of biogeochemical exploration techniques to aid in the exploration for lithium-cesium-tantalum pegmatite dikes: Project description and preliminary observations; *in* Summary of Field Work and Other Activities, 2022, Ontario Geological Survey, Open File Report 6390, p.31-1 to 31-7.

Users of OGS products should be aware that Indigenous communities may have Aboriginal or treaty rights or other interests that overlap with areas of mineral potential and exploration.

© King's Printer for Ontario, 2022

© King's Printer for Ontario, 2022

ISBN 978-1-4868-6588-8 (print)
ISBN 978-1-4868-6589-5 (PDF)

Open File Reports of the Ontario Geological Survey are available for viewing at the John B. Gammon Geoscience Library in Sudbury and at the regional Mines and Minerals office whose district includes the area covered by the report (see below).

Copies can be purchased at Publication Sales and the office whose district includes the area covered by the report. Although a particular report may not be in stock at locations other than the Publication Sales office in Sudbury, they can generally be obtained within 3 working days. All telephone, fax, mail and e-mail orders should be directed to the Publication Sales office in Sudbury. Purchases may be made using cash, debit card, VISA, MasterCard, cheque or money order. Cheques or money orders should be made payable to the *Minister of Finance*.

John B. Gammon Geoscience Library 933 Ramsey Lake Road, Level A3 Sudbury, Ontario P3E 6B5	Tel:	(705) 670-5614
Publication Sales 933 Ramsey Lake Rd., Level A3 Sudbury, Ontario P3E 6B5	Tel: Toll-free: Fax: E-mail:	(705) 670-5691 (local) 1-888-415-9845 ext. 5691 (705) 670-5770 pubsales.ndm@ontario.ca

Regional Mines and Minerals Offices:

Kenora – Suite 104, 810 Robertson St., Kenora P9N 4J2

Kirkland Lake – 1451 Hwy. 66, P.O. Box 40, Swastika P0K 1T0

Red Lake – 227 Howey Street, P.O. Box 324, Red Lake P0V 2M0

Sault Ste. Marie – 740 Great Northern Rd., Sault Ste. Marie P6B 0B4

Southern Ontario – P.O. Bag Service 43, 126 Old Troy Rd., Tweed K0K 3J0

Sudbury – 933 Ramsey Lake Rd., Level A3, Sudbury P3E 6B5

Thunder Bay – Suite B002, 435 James St. S., Thunder Bay P7E 6S7

Timmins – Ontario Government Complex, P.O. Bag 3060, 5520 Hwy. 101 East, South Porcupine P0N 1H0

Every possible effort has been made to ensure the accuracy of the information contained in this report; however, the Ontario Ministry of Mines does not assume liability for errors that may occur. Source references are included in the report and users are urged to verify critical information.

If you wish to reproduce any of the text, tables or illustrations in this report, please write for permission to the Manager, Publication Services, Ministry of Mines, 933 Ramsey Lake Road, Level A3, Sudbury, Ontario P3E 6B5.

Cette publication est disponible en anglais seulement.

Parts of this report may be quoted if credit is given. It is recommended that reference be made in the following form:

Amyotte, E.G., Kurucz, S.V., Paju, G.F., Jonsson, J.R.B. and Kurcinka, C.E. 2022. Investigation of biogeochemical exploration techniques to aid in the exploration for lithium-cesium-tantalum pegmatite dikes: Project description and preliminary observations; *in* Summary of Field Work and Other Activities, 2022, Ontario Geological Survey, Open File Report 6390, p.31-1 to 31-7.

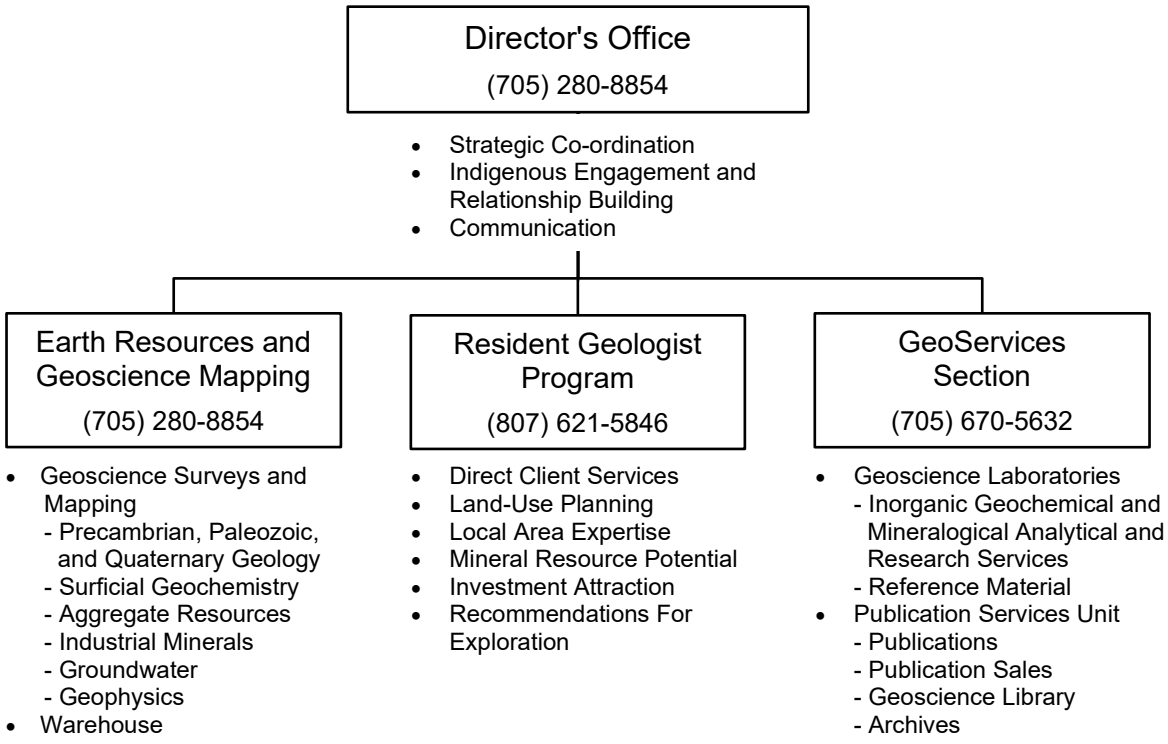


Mines and Minerals Division Regional and District Offices

CITY	ADDRESS	OFFICE(S)	TELEPHONE	FAX
Kenora	Suite 104, 810 Robertson St., Kenora P9N 4J2	○ ■	(807) 468-2813	(807) 468-2930
Red Lake	227 Howey Street, P.O. Box 324, Red Lake P0V 2M0	● ■	(807) 727-3272	(807) 727-3553
Thunder Bay – North Thunder Bay – South	Suite B002, 435 James St. S., Thunder Bay P7E 6S7	● ■ ▼	(807) 475-1332	(807) 475-1112
Sault Ste. Marie	740 Great Northern Road, Sault Ste. Marie P6B 0B4	○ ■	(705) 943-2219	
Timmins	Ontario Government Complex, P.O. Bag 3060, 5520 Hwy 101 East, South Porcupine P0N 1H0	● ■ ▼	(705) 235-1615	(705) 235-1620
Kirkland Lake	1451 Hwy. 66, P.O. Box 40 Swastika P0K 1T0	● ■	(705) 718-8735	
Sudbury	Willet Green Miller Centre, Level A3, 933 Ramsey Lake Rd., Sudbury P3E 6B5	○ ★	(705) 670-5733 (705) 670-5742 *Toll-Free (Canada, USA):* (888) 415-9845	(705) 670-5770 (705) 670-5681 *Toll-Free (Canada, USA):* (877) 670-1444
Tweed (Southern Ontario)	P.O. Bag Service 43, 126 Old Troy Rd., Tweed K0K 3J0	● ■ ▼	(613) 243-0739	(613) 478-2873

Ministry of Mines

Ontario Geological Survey Branch



Contents

Office of the Director, Ontario Geological Survey

1. Ontario Geological Survey: Update of Strategic Perspective for 2022–2023 *S.B. Beneteau*
2. Ontario Geological Survey: Measuring Success *K.J.J. Kalmo*
3. Activities of the Indigenous Geoscience Liaisons in 2021–2022 *M.D. Levesque and D.J. Bennett*

Earth Resources and Geoscience Mapping Section

4. Earth Resources and Geoscience Mapping Section: 2022–2023 Program and Projects Overview *J.H. Hechler, R.M. Easton, S. Préfontaine, M. Duguet, L. Robichaud and R. Cormier*

Precambrian Geology – Northeastern Ontario

5. New Geochronological Data from the Hollinger Mine, Timmins Area, Abitibi Greenstone Belt, Northeastern Ontario *P.J. MacDonald and S.L. Kamo*
6. Project NE-22-003. Preliminary Geology and Mineral Potential of Dore and Swayze Townships and Part of Garnet Township, Swayze Area, Abitibi Greenstone Belt *T.P. Gemmell and A. Buyers*
7. Project NE-18-007. Preliminary Geology of Meath Township, Northeastern Michipicoten Greenstone Belt, Northeastern Ontario *L.E.D. Vice*
8. Project NE-22-002. Introduction to a Geochronological and Structural Study of Supracrustal Assemblages in the Northeastern Michipicoten Greenstone Belt *L.E.D. Vice, S. Perrouty and L. Robichaud*

Precambrian Geology – Northwestern Ontario

9. Project NW-19-001. Highlights of Bedrock Geology Mapping in the Quetico Subprovince, North of Thunder Bay, Northwestern Ontario *R.T. Metsaranta*
10. Project NW-22-001. Precambrian Geology of the Straw Lake–Esox Lake Area, Western Wabigoon Subprovince, Northwestern Ontario *S.R. Meade*

Precambrian Geology – Proterozoic

11. Project NW-22-002. Reconnaissance Bedrock Geology Mapping of the Animikie Basin and Spatially Associated Midcontinent Rift–Related Igneous Rocks, Thunder Bay Area, Northwestern Ontario: A Project Introduction *R.T. Metsaranta and C.E. Kurcinka*
12. Project SO-22-003. Geology of the Grenville Front Tectonic Zone near Sudbury, Northeastern Ontario *R.M. Easton*
13. Project NE-22-001. Preliminary Geology of Hyman Township, Southern and Superior Provinces, Sudbury District, Northeastern Ontario *C.A. Gordon*
14. Project SO-19-001. Preliminary Geology of Patton and Thompson Townships, Iron Bridge Area, Southern Province, Northeastern Ontario *E.C.G. Hastie, P.J. MacDonald and M. Duguet*

Precambrian Geology – Pan-Provincial

15. Project ON-19-004. Trace Element Content of Gold Across Ontario: An Update on the Gold Fingerprinting Project *J.D. Melo-Gómez, E.C.G. Hastie, H.L. Gibson, K.T. Tait and J.A. Petrus*

Geophysics

16. Summary of Geophysical Projects and Activities *S. Biswas and J. Evangelatos*

Surficial Mapping and Sampling

17. Project NE-22-004. Quaternary Geological Mapping of the Lake Nipissing Basin, Highway 17 Corridor, Northeastern Ontario *A.S. Marich*

18. Project SO-19-003. Sediment Mapping in the City of Ottawa, Southeastern Ontario *R.P.M. Mulligan*

Paleozoic Geology and Energy Studies

19. Project SO-20-001. Subsurface Stratigraphy of Early Silurian Medina Group Mixed Siliciclastic–Carbonate Strata, Southwestern Ontario: Final Update *R.H. Paterson, F.R. Brunton, J. Jin, A.R. Phillips and K.H. Yeung*

20. Project SO-21-002. Stratigraphy and Sedimentology of Upper Ordovician Strata, with Emphasis on the Collingwood and Rouge River Members, Southern Ontario and Manitoulin Island *D. Atasiei, C.J. Tsujita, F.R. Brunton, J. Jin and K.H. Yeung*

21. Project SO-22-004. Revisiting the Cambrian Stratigraphy of Southwestern Ontario *A.R. Phillips, F.R. Brunton and K.H. Yeung*

22. Project SO-22-001. Paleozoic Geology of the Kingston Area, Eastern Ontario *K.E. Hahn*

23. Project SO-22-002. Paleozoic Geology of Eastern Ontario: Russell–Thurso Area *C. Béland Otis*

Groundwater Studies

24. Project SO-22-005. From Mighty Moraines to Dramatic Drumlins: Introducing the Guelph Three-Dimensional Sediment Mapping Project *A.K. Burt and G.W. Hagedorn*

25. Project SO-22-006. South Ottawa Groundwater Study, Eastern Ontario *T. Di Iorio, S. Foubister and C.N. Bocking*

Geoscience Laboratories

26. Osmium Analysis at the Geoscience Laboratories by Nickel Sulphide Fire Assay with Inductively Coupled Mass Spectrometric Finish *O.M. Burnham*

27. Expansion of the Capabilities of the Geoscience Laboratories Methods for the Analysis of Trace Elements Important to Ontario's Critical Minerals Strategy *O.M. Burnham*

28. Summary of Quality Control Data for the Geoscience Laboratories Methods IMC-100, IMO-100 and IMP-101 *J.C. Hargreaves*

29. Revision of the Calibration for Trace Element Analysis of Geological Samples by Wavelength Dispersive X-Ray Fluorescence at the Geoscience Laboratories *G.L. Keating*

Resident Geologist Program

30. Identification of Fertile Parent Granitoid Units in the Superior Province of Ontario: Project Description *R.M. Cundari*

31. Investigation of Biogeochemical Exploration Techniques to Aid in the Exploration for Lithium-Cesium-Tantalum Pegmatite Dikes: Project Description and Preliminary Observations *E.G. Amyotte, S.V. Kurucz, G.F. Paju, J.R.B. Jonsson and C.E. Kurcinka*

32. Catching it by the Tailings: An Introduction to the Ontario Geological Survey Critical Minerals Mine Waste Sampling Project *D.J. Bennett*

33. Geology, Geochemistry and Mineralogy of the Enid Creek Cobalt-Copper-Nickel-Palladium-Platinum Prospect, Loveland Township, Northwest of Timmins, Ontario *E.H. van Hees, S.A. Clarke, D.C. Crabtree, A.S. Péloquin and Z. Azadbakht*

Index of Authors

Metric Conversion Table

This page left blank intentionally

Office of the Director, Ontario Geological Survey

1. Ontario Geological Survey: Update of Strategic Perspective for 2022–2023



S.B. Beneteau[1]

[1]Director's Office, Ontario Geological Survey, Sudbury, Ontario P3E 6B5

INTRODUCTION

This article provides an update on the strategic direction of the Ontario Geological Survey (OGS) based on activities during the 2022–2023 fiscal year.

These strategic priorities include the delivery of relevant, accurate, up-to-date public geoscience data and information about Ontario in order to

- identify economic opportunities;
- safeguard public health and safety related to natural geological factors; and
- inform environmental and land-use planning decisions.

As part of delivering on the strategic plan, the OGS continues to address government priorities and provides public geoscience to the general public, stakeholders and Indigenous partners. This is done to inform and guide decision making in the areas of mineral investment attraction and Earth resources management, land-use planning, healthy communities and energy supply.

THE ONTARIO GEOLOGICAL SURVEY

The OGS is the principal provincial government organization responsible for the collection, interpretation, documentation and dissemination of public geoscience data and information. The geoscience expertise of the OGS focusses on the description of Ontario's bedrock geology, surficial geology, the geological processes that shaped the landscape, and the Earth resources (groundwater, minerals, metals, aggregates, hydrocarbons) that occur within the geological framework. This public geoscience information is used to support and inform decisions related to

- environmental geochemical baseline;
- identification and description of naturally occurring geological hazards that may pose a threat to public health and safety;
- engineering infrastructure factors related to aggregates and terrain;
- changing climate impact and mitigation considerations;
- land-use planning and Earth resources management from a geological perspective;
- biodiversity and habitat as they relate to geology; and
- economic development and stewardship related to groundwater, energy, aggregates, metals and minerals.

Summary of Field Work and Other Activities, 2022,
Ontario Geological Survey, Open File Report 6390, p.1-1 to 1-12.

© King's Printer for Ontario, 2022

The waning of the COVID-19 pandemic provided an opportunity for the OGS to return to a fulsome field season. The OGS continues to generate world-class geoscience information, products and services, including the 33 articles in this volume and numerous other publications released by OGS staff. The Resident Geologist Program (RGP) continued to provide information and support to the exploration sector and are on target to release *Recommendations for Exploration 2022–2023* in late January 2023. The Geoscience Laboratories continued to function throughout 2022, providing valuable, high-quality geoanalytical data to the Ontario Geological Survey.

VISION, MISSION AND MANDATE OF THE ONTARIO GEOLOGICAL SURVEY

The OGS vision, mission and mandate statements are as follows:

Vision: The OGS is "a leading provider of reliable, credible, accessible public geoscience data, information and expert knowledge for the public good".

Mission: The OGS sustains and supports Ontario's quality of life, economic prosperity, environmental quality and public safety by providing Ontario's citizens, institutions and Indigenous Peoples with public geoscience data, information and expert knowledge to inform decision making.

Mandate: The OGS collects and disseminates public geoscience data and information and provides expert knowledge to attract and guide mineral sector investment, as well as inform a broad range of government policy priorities, including mineral investment attraction, land use planning, healthy communities, and energy supply.

ONTARIO GEOLOGICAL SURVEY: DELIVERING GLOBALLY SIGNIFICANT PUBLIC GEOSCIENCE

The OGS has maintained an international reputation for independent, credible, public geoscience expertise. The following examples highlight recent achievements of OGS technical professionals:

- publication of the volcanic stratigraphy of the western Schreiber–Hemlo greenstone and Mesoproterozoic geology of the north shore of Lake Superior (Open File Report 6377);
- publication of new geochronological data from the Hollinger Mine, Timmins, Abitibi greenstone belt, northeastern Ontario (this volume, Article 5);
- publication of geochronological sampling of supracrustal assemblages in the northeastern Michipicoten greenstone belt, northeastern Ontario (this volume, Article 8);
- publication of the preliminary geology of Meath Township, northeastern Michipicoten greenstone belt, northeastern Ontario (this volume, Article 7);
- publication of the preliminary geology of Swayze, Dore and Garnet townships, Swayze area, Abitibi greenstone belt, northeastern Ontario (this volume, Article 6);
- update on bedrock mapping of the southern Quetico Subprovince and the Midcontinent Rift north of Thunder Bay, northwestern Ontario, with emphasis on the geology of peraluminous granitoids and related granitic pegmatites (this volume, Article 9);
- publication of the Precambrian geology of the Straw Lake–Esox Lake area, northwestern Ontario (this volume, Article 10);
- publication of the compilation and reconnaissance-style bedrock mapping of the Animikie Basin and Midcontinent Rift southwest of Thunder Bay, northwestern Ontario (this volume, Article 11);

- publication of the geology of the Grenville Front tectonic zone near Sudbury, northeastern Ontario (this volume, Article 12);
- publication of the preliminary geology of Hyman Township, Southern and Superior provinces, Sudbury district, northeastern Ontario (this volume, Article 13);
- publication of the preliminary geology of Patton and Thompson townships, Iron Bridge area, Southern Province, northeastern Ontario (this volume, Article 14);
- update on the gold fingerprinting project of the trace element content of gold across Ontario (this volume, Article 15);
- publication of Quaternary geological mapping of the Lake Nipissing Basin, northeastern Ontario (this volume, Article 17);
- publication of sediment mapping in the city of Ottawa, southeastern Ontario (this volume, Article 18);
- publication of a final update on the subsurface stratigraphy of early Silurian Medina Group mixed siliciclastic–carbonate rocks, southwestern Ontario (this volume, Article 19);
- publication of Upper Ordovician stratigraphy and sedimentology of the Collingwood and Rouge River members, southern Ontario and Manitoulin Island (this volume, Article 20);
- publication of the Cambrian stratigraphy in southwestern Ontario (this volume, Article 21);
- publication of the Paleozoic geology of the Russell–Thurso area (this volume, Article 23) and the Kingston area, eastern Ontario (this volume, Article 22);
- publication of tritium in shallow groundwater in southern Ontario (Groundwater Resources Study 20);
- publication of the regional-scale groundwater geoscience in southern Ontario 2022 Open House program and abstracts (Open File Report 6379);
- publication of south Ottawa groundwater study (this volume, Article 25);
- publication of the project description and preliminary observations of the identification of fertile parent granitoid units in the Superior Province of Ontario (this volume, Article 30);
- publication of the project description and preliminary observations of the investigation of biogeochemistry exploration techniques to aid in the exploration for lithium-cesium-tantalum pegmatite units (this volume, Article 31);
- publication of the project description and preliminary observations of the investigation of mine waste sampling for critical minerals (this volume, Article 32);
- publication of the geology, geochemistry and mineralogy of the Enid Creek copper-nickel-palladium-platinum-cobalt prospect, Loveland Township, northwest of Timmins, Ontario (this volume, Article 33);
- publication of *An Introduction to Ontario's Critical Minerals, with Highlights from the Ontario Mineral Inventory*;
- publication of *Recommendations for Exploration Special Edition: Critical Minerals Compilation 2000–2022*;
- publication of 4 Index Miscellaneous Papers containing information reports, maps and digital data published from 2011 to 2020;
- ongoing delivery of the services of a world-class inorganic geochemical laboratory, which supports the OGS geochemical program;

- publication of 4 geological field trip guidebooks for the Sudbury and Elliot Lake areas in conjunction with the Institute on Lake Superior Geology; and
- ongoing delivery of the Resident Geologist Program (RGP), which delivers local expert geoscience knowledge and front-line service to clients, stakeholders, Indigenous Peoples and the general public across Ontario.

To date, the active OGS public geoscience information holdings include 10 352 maps, 3357 reports and 670 data releases. In the period November 1, 2021 to September 30, 2022, the OGS published 14 new reports, 0 new maps, and 3 new data releases.

From November 1, 2021, to October 21, 2022, numerous publications and data files were downloaded or accessed:

- downloaded from our GeologyOntario Web site:
  - in excess of 401 945 maps and reports in portable document format (*.pdf*) and image (*.jpg*) format
  - 11 975 compressed (*.zip*) files
- downloaded from our OGSEarth Web site:
  - 44 363 master *.kml* and/or *.kmz* files
  - Resident Geologist Program databases and recommendations
    - Ontario Mineral Inventory (OMI) 1025 *.zip* files
    - Ontario Assessment File Database (OAFD) 736 *.zip* files
    - Ontario Drill Hole Database (ODHD) 725 *.zip* files
    - *Recommendations for Exploration* 3558 *.pdf* files, including the Special Edition Critical Minerals compilation
      The current *2021–2022 Recommendations for Exploration* was 457 (12.8%), 2005–2021 was 2008 (56.4%), and the Special Edition Critical Minerals Compilation was 1091 (30.7%).
- downloaded, viewed and accessed from our OGSEarth RGP Activity Reports—Mineral Exploration (AR—ME), compiled by the district offices:
  - AR—ME *.kml* file on OGSEarth Web page downloaded 1119 times
  - AR—ME Web page list viewed 1005 times
  - individual pages for the district offices accessed 3222 times
    (through the AR—ME Web page list)

CURRENT TRENDS THAT WILL SHAPE THE FUTURE OF THE ONTARIO GEOLOGICAL SURVEY

Trends that continue to influence the OGS geoscience program include the following:

- Long-term global growth, largely driven by the need for mineral resources: having up-to-date inventories of Ontario's geology and Earth resources is a key aspect of attracting and fulfilling this investment potential.
- Mineral resource exploration and development continue to push geographic and technological frontiers: the Far North, "deep search" for mineral resources, potential for renewable and non-renewable energy sources, and quality and quantity of groundwater resources.

- Expectations for governments to provide robust guidance on management, mitigation and adaptation to the challenges of a changing climate require geoscience to help frame and inform some of those decisions, including drought mitigation and the identification and protection of vulnerable groundwater aquifers.
- Population growth across southern Ontario, which requires geoscience for land-use planning and the identification of groundwater aquifers and aggregate construction materials.
- Emphasis on evidence-based decision making requiring the inclusion of geoscience to fully assess risk and to support decision making.
- Increasing societal need to understand, identify and reduce disaster risks posed by natural geological features and, in a geological context, protect Ontario's natural environments. For each action, the OGS has a vital role to play in ensuring Ontario is well positioned to face these challenges through the provision of geological data and information.
- Standards and expectations for environmental responsibility continue to grow. A sound understanding of the geological features of the Earth is critical to ensuring a geochemical baseline is in place, that the material to be sampled for geochemical analysis is understood, and that the "geological container" that holds the Earth resources, such as groundwater, is described.
- Land-use planning across the Far North and municipalities elsewhere in Ontario will continue; that process requires the consideration of geology in order to assess health, safety, infrastructure, geochemical baseline, source water protection and economic potential options.
- Expectations for rapid, evidence-based policy analysis and user-friendly data discovery, access and handling will continue to grow through an "open spatial data" climate.
- Engagement, relationship-building, collaboration and notification of Indigenous Peoples and citizens of Ontario related to the delivery of OGS geoscience project activities is an essential part of operating with a social licence and is an integral part of the operations of the OGS geoscience program where a multi-year presence on the land is required.
- Jurisdictions across the globe have started assessing not only the vulnerability of their respective economies to the supply of critical minerals, but also to the availability within their borders. The OGS is positioned to provide the geoscience knowledge, data and information to support exploration and understanding of critical minerals in Ontario.
- Ontario's Critical Minerals Strategy, launched in March 2022, provides an opportunity for the OGS to play a key role in enhancing geoscience information and supporting critical minerals exploration in the province.

ONTARIO GEOLOGICAL SURVEY CLIENTS AND STAKEHOLDERS

The OGS works closely with Indigenous Peoples in anticipated and planned geoscience project areas to engage, to build meaningful relationships and to discuss potential impacts and implications of OGS projects. The OGS practice is to work collaboratively with Indigenous communities on topics of mutual interest that can be the basis of a collaboration and/or partnership related to a geoscience project. This practice has matured since the OGS implemented changes in 1999 to its Indigenous engagement practices. In 2016, the OGS Director's Office recruited 2 Indigenous Geoscience Liaison positions based in Sudbury and Thunder Bay. A summary of the activities of the Indigenous Geoscience Liaisons during 2021–2022 are described by Levesque and Bennett (this volume, Article 3).

The OGS also has clients who formulate and implement policy and who are regulators in provincial, municipal and local governments. In 2021–2022, the OGS continued to support the application of

geoscience information into broader government decision making by guiding other provincial ministries in applying public geoscience to help inform their decisions. The OGS continues the ongoing strengthening of collaboration and communication among government geoscientists and users of geoscience, through co-ordinated cross-ministry efforts that support the exchange of information, and at expanding the knowledge and expertise with respect to the application of geoscience in government.

In addition, public geoscience data, information and knowledge are used by municipalities, academia and a variety of private sector organizations to inform business-related decisions. The OGS conducts annual client surveys (*see* Kalmo, this volume, Article 2) to measure 6 performance indicators including the percentage of decision makers who state that their use of OGS products and services increased their decision-making efficiency and effectiveness by focussing their efforts on areas of interest identified by public geoscience. The performance and effectiveness of the OGS geoscience program, based on client input, is measured and tracked from year to year (*see* Kalmo, this volume, Article 2).

CURRENT STRATEGIC PRIORITIES

Four strategic priorities continue to be the focus of the OGS for fiscal year out to 2023.

What Will the OGS Do Strategically?

- **Priority 1** Establish a geoscience baseline for all of Ontario in order to identify economic opportunities, safeguard public health and safety, and inform environmental and land-use planning decisions.
- **Priority 2** Contribute to the maintenance and enhancement of Indigenous relations.
- **Priority 3** Contribute to mineral development investment attraction.
- **Priority 4** Inform users about the value and relevance of OGS goods and services.

Results to Date

PRIORITY 1

Priority 1. Establish a geoscience baseline for Ontario in order to identify economic opportunities, safeguard public health and safety, and inform environmental and land-use planning decisions.

Strategic Objective: Provide modern, independent and credible geoscience data, information and knowledge to support decision making by government, Indigenous communities, citizens and industry.

Ontario Geological Survey public geoscience goods and services provide support for economic, social and environmental public policy decisions in a variety of areas:

- Economy: metal, mineral (including aggregate), water (groundwater) and energy resources;
- Environment: inorganic geochemical baseline, geological habitat that influences biodiversity, waste management and climate change mitigation and adaptation;
- Public health and safety: groundwater quality; geological hazards (e.g., landslides, karst, geochemical, gas, radioactivity); and
- Community: infrastructure planning, land-use planning, resource stewardship.

Multi-year priorities are established and reviewed annually during the OGS project planning process. The Geological Survey of Canada (Natural Resources Canada–Lands and Minerals Sector) is also an important part of the annual geoscience priority planning. These inputs are in addition to geoscience needs that are identified by public and private stakeholders and clients. The resulting geoscience projects are distributed across all of Ontario (*see* Hechler et al., this volume, Article 4).

Results

To deliver on the strategic priorities, different roles and responsibilities are distributed across the OGS Branch (Table 1.1). Some notable results of the key technical mapping commitments are the following:

- two- and three-dimensional geological mapping projects continued in various regions across Ontario to attract mineral investment, to inform land-use planning related to Indigenous communities and municipalities in northern and southern Ontario, to assess mineral, energy and groundwater resource potential and to support resource and infrastructure development decisions
- published geochemical survey data, including groundwater characterization, to continue to assist in the identification of natural factors in the environment, water-quality issues and geohazards
- continuing updates to the Ontario Mineral Inventory (OMI) and its online database
- continuing updates to the Aggregate Resources of Ontario (ARO) database
- continuing updates to the Geochronology Inventory of Ontario (GeochrON) database

A number of technical initiatives are achieving these results (*see* Hechler et al., this volume, Article 4).

PRIORITY 2

Priority 2. Contribute to building collaborative relationships with Indigenous communities.

Strategic Objective: Continue to maintain and build meaningful and respectful relationships with Indigenous Peoples and organizations as a foundation for OGS geoscience program activities.

Within the Ministry of Mines, Mines and Minerals Division, the OGS contributes to the Divisional and Ministry goal to engagement and relationship-building with Indigenous Peoples, at a community level, and with organizations (Table 1.2).

Results

Focus during the 2022–2023 fiscal year was to continue collaborations and relationship building with Moose Cree First Nation, Fort William First Nation, Taykwa Tagamou First Nation, Missanabie Cree First Nation, Sheshegwaning First Nation, Brunswick House First Nation, Michipicoten First Nation, Mohawks of the Bay of Quinte, Red Sky Métis Independent Nation, Naicatchewenin First Nation, Chapleau Cree First Nation, Mississaugi First Nation, Chapleau Cree First Nation, Algonquins of Ontario, Mohawks of Akwesasne, Mushkegowuk Tribal Council, and Anishinabek Nation (*see* Levesque and Bennett, this volume, Article 3).

The Director's Office includes 2 Indigenous Geoscience Liaison positions based in Sudbury and Thunder Bay. These positions report to the Director and engage, build and maintain relationships with Indigenous Peoples in remote and non-remote communities across Ontario.

Table 1.1. Summary of OGS strategic objectives for public geoscience.

Strategic Objectives – Public Geoscience Information				
Outcomes	**Strategic Objectives**	**Activities**	**How?**	**Who? ***
Ontario geoscience portfolio recognized as a relevant resource to inform economic opportunities, health and safety, environmental and land-use planning decisions Land-use and environmental decisions informed by public geoscience Mineral investment decisions informed by public geoscience Enhanced efficiency and effectiveness and reduced risk of economic investment decisions and land-use and environmental decisions Public awareness about the value and relevance of public geoscience	Establish a geoscience baseline for Ontario to identify economic opportunity	Establish geoscience priorities based on public policy direction and input from stakeholders and clients	Gap analysis meetings with external clients, stakeholders, and with OGS staff who serve as proxy for external clients	Director's Office, ERGMS, RGP
			Project planning	ERGMS, RGP, GeoServices
	Establish a geoscience baseline for Ontario to safeguard public health and safety	Collect, analyze, advise and archive geoscience information	Mapping (OGS and collaborative projects with external collaborators or other governments)	ERGMS, GeoServices, RGP
			Property or site visits: mineral and aggregates	RGP
			Geochemistry	ERGMS, RGP, GeoServices
			Geophysics	ERGMS
			Receive third-party geoscience information	RGP, ERGMS
			Geoscience Library	GeoServices
	Establish a geoscience baseline for Ontario to inform environmental and land-use planning decisions	Provide access to OGS geoscience goods and services in a form that meets client needs	Geoscience Library	GeoServices
			GeologyOntario, OGSEarth and OGS Geoscience Atlas	GeoServices, RGP, ERGMS
			OGS expert technical staff participation in third-party technical meetings	ERGMS, RGP, GeoServices
		Inform users about the value and relevance of OGS goods and services and facilitate application of public geoscience to address priority issues faced by government, industry, and citizens	Multi-ministry committees	Director's Office, ERGMS, GeoServices, RGP, other MINES business units
			Provide geoscience information at technical meetings, symposia, workshops, and through direct client visits	ERGMS, RGP, GeoServices

***Abbreviations:** MINES = Ministry of Mines; ERGMS = Earth Resources and Geoscience Mapping Section; GeoServices = GeoServices Section; OGS = Ontario Geological Survey; RGP = Resident Geologist Program.*

Table 1.2. Strategic objectives for Indigenous relations.

Strategic Objectives – Indigenous Relations				
Outcomes	**Strategic Objectives**	**Activities**	**How?**	**Who? ***
Strong and meaningful relationships between Mines and Indigenous Peoples and organizations	Continue to maintain and build meaningful and respectful relationships with Indigenous Peoples and organizations as a foundation for OGS geoscience program activities	Engagement and relationship-building with Indigenous Peoples, at a community level, and with organizations	Seek social licence for OGS geoscience projects through engagement and relationship-building Offer OGS geoscience topic area expertise Raise awareness about geoscience and its application to Indigenous interests Help build capacity related to geoscience and mineral industry-related careers Serve as a bridge between Indigenous Peoples and government and non-government topic experts	Director's Office, ERGMS, RGP

****Abbreviations:** Mines = Ministry of Mines; ERGMS = Earth Resources and Geoscience Mapping Section; OGS = Ontario Geological Survey; RGP = Resident Geologist Program.*

PRIORITY 3

Priority 3. Contribute to mineral development investment attraction.

Strategic Objective: The OGS contributes to 2 mineral investment-related objectives that are the primary responsibility of the Mines and Minerals Division (MMD), Strategic Services Branch:

- promoting the products and services of Mines and Minerals Division, as well as promoting Ontario's geology through educational and/or informational tools;
- monitoring Ontario's exploration and mining industries and providing information and/or data and analysis on Ontario's mineral sector.

The OGS participates in the promotion of mineral development opportunities in Ontario by promoting the geology and mineral potential of the province, as well as the public geoscience data and information resources. The OGS brings geoscience data, information and expert knowledge to the investment attraction and promotional activities led by the Strategic Services Branch (Table 1.3).
In addition, OGS technical experts support the investment attraction efforts by providing

- geoscience knowledge of available mineral properties in a region;
- knowledge of Ontario geology and the potential for different types of mineral resource opportunities across all of Ontario (for example, regional geochemical maps that highlight areas of enhanced mineral potential); and
- knowledge of key players in the mineral industry and facilitating relationships between interested clients.

Table 1.3. Strategic objectives for mineral development investment and opportunities.

Strategic Objectives – Mineral Development Investment and Opportunities				
Outcomes	**Strategic Objectives**	**Activities**	**How?**	**Who? ***
Identification of investment opportunities and/or advantages that maximize mineral resource potential for Ontario's economic development Sustain and increase investment in Ontario's mineral sector	Promote the products and services of Mines and Minerals Division and Ontario's geology Monitor Ontario's exploration and mining industries Provide data and analysis on the mineral sector	Identify, assess, and promote mineral investment opportunities to industry (and local governments, conservation authorities, and groundwater-related interest groups)	Participate in provincial, national and international marketing and promotional events	RGP, ERGMS, GeoServices, Director's Office

Abbreviations: *ERGMS = Earth Resources and Geoscience Mapping Section; GeoServices = GeoServices Section; RGP = Resident Geologist Program.*

Results

The staff of the OGS participated virtually at the Association for Mineral Exploration (AME) Annual Mineral Exploration Roundup 2022, co-hosted the 2022 Ontario Geological Survey, Geological Survey of Canada, and Conservation Ontario Geoscientists Open House and participated virtually and/or in-person at the Prospectors and Developers Association of Canada (PDAC) 2022 Annual Convention. Staff also co-chaired the Institute on Lake Superior Geology meeting held at Science North in Sudbury in May 2022, led 4 geological field trips, and edited the associated Program and Abstracts and Field Trip Guidebook volumes. Staff participated virtually in the Canadian Exploration Geophysical Society Symposium 2022; Geological Society of America Connects 2022 annual conference; the 2022 Inductively Coupled Plasma (ICP) Conference; Society of Economic Geologists Conference; and the Québec Mines + Énergie 2022 conference. Staff participated in-person at the Canadian Mining Expo 2022, and Central Canada Resource Expo 2022.

PRIORITY 4

Priority 4. Inform users about the value and relevance of OGS goods and services.

Strategic Objective: The objective is to raise awareness and understanding about the relevance, value and application of OGS public geoscience to inform decision-making for government, clients, stakeholders, Indigenous Peoples and the public.

The OGS role is to communicate the existence, relevance and application of public geoscience and provide a broad range of products and services to deliver geoscience information to users, including two- and three-dimensional geological maps, reports, data sets and databases, technical posters, technical presentations, and expert knowledge and advice.

All geoscience publications are available for free download through the GeologyOntario online data warehouse (www.mndm.gov.on.ca/en/mines-and-minerals/applications/geologyontario). Some key data sets are also available through OGSEarth (www.geologyontario.mndm.gov.on.ca/ogsearth.html), which uses the Google Earth™ mapping service to view public geoscience data and information in a geographic context. The Resident Geologist Program (RGP) has also enhanced access to data using OGSEarth by adding mineral deposit and assessment file information, as well as increasing online accessibility to non-assessment geoscience information in the RGP offices.

Results

The OGS continued to use a variety of communication channels to deliver its products, raise awareness about geoscience and improve access to data, including

- "social media", such as Twitter®, Facebook®, and Linkedln® professional networking service, and internal communication channels;
- formal public presentations that describe the value, relevance and application of geoscience;
- improving the Ontario Mineral Exploration Information System, which is an internal process to improve and streamline processing and uploading of assessment files, drill-hole data and other geoscience information; and
- launch of a new GIS-based product (OGS Data Grid Layer) to provide easy, rapid access to OGS data and map products through spatial searches.

Priorities Linked to Ontario's Critical Minerals Strategy

Ontario's Critical Minerals Strategy, which is a five-year strategy, comprises 6 pillars that will solidify Ontario's position as a global leader of responsibly sourced critical minerals. The OGS plays a foundational role in Pillar 1 - Enhancing Geoscience Information and supporting critical minerals exploration. To date, 9 OGS activities have been initiated or completed in support of Ontario's Critical Minerals Strategy (Table 1.4).

Table 1.4. OGS activities in support of Ontario's Critical Minerals Strategy.

Goal	Geoscience Activity	Status
Releasing innovative, new geospatial data products that provide quicker, easier access to OGS geoscience data	Release of new Critical Mineral Ontario Mineral Inventory geospatial products	Completed
	Release of OGSFocus and OGS GeoData Listing through OGSEarth	Completed
Introduce a modernized digital platform for mineral exploration companies to access Ontario's critical minerals geoscience information from anywhere in the world	The Ontario Geological Survey (OGS) and the Information and Lands Branch (ILB) are collaborating to develop a new GeologyOntario application	Target completion spring of 2023
Introduce new products that improve compilation and interpretation of existing OGS data, combined with digitizing archival information	Introduction to Ontario's Critical Minerals publication	Completed
	Release of OGSFocus and OGS GeoData Listing through OGSEarth	Completed
Reassessing historical geoscience information to better identify critical minerals deposits	Recommendations for Exploration *Special Edition* – Critical Minerals Compilation 2000-2022 published	Completed
Undertake new geoscience initiatives that target underexplored areas of Ontario in partnership with Indigenous communities where potential partnership opportunities may exist	New airborne geophysics, bedrock mapping projects, lake sediment surveys in underexplored areas of Ontario with high critical mineral potential	Ongoing (this volume, Articles 9, 30 and 33)
	Recommendations for Exploration published	Completed annually
Initiate a mine waste sampling project to help identify critical mineral content in tailings and waste rock, to support redevelopment of historic deposits	An introduction to the critical minerals mine waste sampling project	Completed (this volume, Article 32)

THE FUTURE

Building on the work initiated in 2018–2019, the OGS management team continues implementing the OGS five-year strategic plan.

The OGS continues to:

- implement a geoscience program based on accurate, modern, credible, public geoscience data, information and knowledge to help inform decision making;
- identify naturally occurring geological features and phenomena relevant to public health and safety;
- publish and promote information about Ontario's Earth resources, including its mineral, energy and water resource endowments;
- develop new geoscience products that help present our complex geoscience data in a form that is understood by non-geoscience users, including the development of products that broaden the access and awareness of OGS geoscience goods and services to both traditional and non-traditional users;
- utilize social media.

The OGS public geoscience goods and services play an important role in helping support public-policy decision makers, investors and other users. Societal needs are increasingly complex and require a sound and objective understanding of geoscience to help assess and frame the complex options available. Geoscience is an essential element of social, environmental, and resource management decision-making processes.

STAFFING CHANGES IN THE DIRECTOR'S OFFICE

In October 2021, Kayla Kalmo joined the Director's office on a six-month training and development assignment as the Project and Results Management Coordinator. In July 2022, Kayla Kalmo secured an additional six-month term as the Project and Results Management Coordinator. In February 2022, Darla Bennett joined the Director's Office as an Indigenous Geoscience Liaison for 6 months. In September 2022, Darla Bennett permanently secured the position of Indigenous Geoscience Liaison. In March 2022, Lesley McAdam secured the Administrative Assistant position in the Director's Office on a twelve-month contract basis.

2. Ontario Geological Survey: Measuring Success



K.J.J. Kalmo[1]

[1]Director's Office, Ontario Geological Survey

INTRODUCTION

The Ontario Geological Survey (OGS) Branch has 3 program outcomes:

- Short-Term Outcome: Clients, stakeholders and Indigenous communities have awareness of the value, relevance and application of available geoscience information;
- Intermediate Outcome: Geoscience knowledge and information are valued and used to inform decisions related to economic, environmental and social priorities;
- Long-Term Outcome: People and communities in Ontario benefit from the informed use of Ontario's land and Earth resources.

To help achieve these outcomes, as well as to measure program success, the OGS has 6 performance indicators that it measures and tracks.

1. Percentage of decision makers who state that their use of OGS products and services increased their decision-making efficiency and effectiveness by focussing their efforts on areas of interest identified by OGS geoscience.
2. Percentage of decision makers who used OGS products and services to support their mineral investments or environmental decisions.
3. Percentage of decision makers who were satisfied with OGS products and services to support their decision making.
4. Indigenous communities who were satisfied with OGS products and services.
5. Percentage of clients and stakeholders satisfied with value-added OGS geoscience information (e.g., laboratory services, publication services, prospecting courses, groundwater meetings).
6. Annual number of square kilometres mapped by OGS based on results of OGS project proposal evaluation process.

The OGS conducts a large annual client survey by e-mail to measure each of the performance indicators. Performance is also measured by surveying participants who attend OGS presentations and information sessions; documenting the completion of major project milestones; and documenting testimonials from Indigenous communities. All of these data are collected, tracked and monitored to ensure that the OGS is providing high-quality, relevant geoscience products and services to its clients, stakeholders, Indigenous Peoples and the general public.

Summary of Field Work and Other Activities, 2022,
Ontario Geological Survey, Open File Report 6390, p.2-1 to 2-8.

© King's Printer for Ontario, 2022

VALUE-ADDED PRODUCTS AND SERVICES

The Resident Geologist Program (RGP) and the GeoServices Section of the OGS conduct client surveys that are specific to their program areas. The RGP distribute hard-copy surveys at regional offices and at various tradeshows and conferences that they attend. However, because of the COVID-19 pandemic throughout 2020 and 2021, the RGP has not had the opportunity to distribute these surveys and, therefore, did not collect any data for this year (Table 2.1).

The GeoServices Section uses SurveyMonkey® software to distribute client surveys and collect results (*see* Table 2.1).

The OGS, in collaboration with the Geological Survey of Canada and Conservation Ontario, conducts an annual Regional-Scale Groundwater Geoscience Open House in Southern Ontario. Participants are surveyed on their overall satisfaction with the event, using hard-copy surveys and SurveyMonkey®, and results are recorded (*see* Table 2.1).

Table 2.1. Client survey results from the Resident Geologist Program, GeoServices Section and the Groundwater Open House.

Survey Question	Program Area	2015–2016	2016–2017	2017–2018	2018–2019	2019–2020	2020–2021	2021–2022
How satisfied are you with the RGP products and services	Resident Geologist Program	n/a	79%	94%	96%	100%*	n/a	n/a
How satisfied are you with the analyses and services provided by the Geoscience Laboratories	GeoServices Section	84%	n/a	83%	97%	99%	100%*	87%*
Please rate your overall satisfaction with the Groundwater Open House	Groundwater Open House	n/a	94%	93%	99%	100%	93%	92%

n/a = no data available.
** Less than 40 respondents*

ANNUAL CLIENT SURVEY

Method

The 2021–2022 OGS Client Survey was conducted from March 15 to April 14, 2022. A database of 718 clients was compiled by OGS staff, with 630 of these clients having valid contact information. The survey was conducted using SurveyMonkey®, an online survey platform that is used to create and distribute surveys and collect and analyze results. This approach involved sending electronic invitations through the software to respondents, who had e-mail addresses provided for them, to complete the survey online. A total of 5 follow-up reminders were then sent to those who did not complete the survey.

A total of 275 responses were captured, a 44% response rate. This response was a 1% increase from the 2021 results and remains consistent with rates of previous years (lowest to highest: 40–53%). Another factor to consider is the sample size being the largest of all years, also resulting in the number of responses (N=275) being the highest received within the 9 years the survey has been completed.

Survey Results

Ten questions were asked of 2 major OGS client groups: 1) mineral or other resource exploration and/or development; and 2) land-use planning, groundwater or environmental. These clients were further separated into A) product users and B) service users. It should be noted, however, that this was the fourth year clients were divided into these categories; therefore, the results may be skewed in the representation to years previous to 2019. Also note that clients were able to identify as solely using products, solely using services, or a user of both products and services—this separation began in 2019 as well. The results of each category are noted below in Table 2.2 for questions asked of all clients, Table 2.3 for questions asked of clients who identified as product users, and Table 2.4 for those clients who identified as service users.

Table 2.2. Ontario Geological Survey 2021–2022 client survey questions and summary of results for OGS clients.

Survey Question	Mineral / Resource / Exploration							
	2014–2015	2015–2016	2016–2017	2017–2018	2018–2019	2019–2020	2020–2021	2021–2022
What category best describes the majority of work that you conduct?	66%	65%	72%	77%	80%	72%	84%	83%
How would you rate your overall satisfaction with the OGS?	85%	80%	85%	73%	81%	86%	83%	84%

Survey Question	Land-Use Planning / Groundwater / Environmental							
	2014–2015	2015–2016	2016–2017	2017–2018	2018–2019	2019–2020	2020–2021	2021–2022
What category best describes the majority of work that you conduct?	34%	35%	28%	23%	20%	28%	16%	17%
How would you rate your overall satisfaction with the OGS?	95%	94%	93%	96%	90%	96%	86%	95%

Table 2.3. Ontario Geological Survey 2021–2022 client survey questions and summary of results for OGS product users.

Survey Question	Mineral / Resource / Exploration							
	2014–2015	2015–2016	2016–2017	2017–2018	2018–2019	2019–2020	2020–2021	2021–2022
Percentage of clients who used OGS products within the past 12 months?	90%	94%	90%	89%	94%	92%	84%	93%
Overall satisfaction with the quality of OGS products	n/a	n/a	88%	79%	80%	85%	86%	90%
Percentage of clients who used OGS products to make a decision	69%	80%	68%	54%	57%	50%	62%	63% [1]
Did OGS products allow clients to focus their efforts on areas of higher potential and/or interest?	74%	76%	73%	50%	62%	77%	76%	74% [2]
Did OGS products reduce the time and cost to advance to the next stage of exploration or decision making?	61%	65%	50%	38%	32%	33%	32%	38% [2]
Did the use of OGS products improve clients' exploration models or strategies?	80%	76%	55%	46%	40%	46%	51%	54% [3]
Did the use of OGS products reduce clients' decision risks?	74%	65%	60%	39%	28%	34%	36%	33% [3]
Did the use of OGS products/services provide evidence of the presence or absence of critical features, target deposit type or topic of interest?	72%	57%	59%	41%	43%	48%	46%	51% [3]

Table 2.3, *continued*.

Survey Question	Land-Use Planning / Groundwater / Environmental							
	2014–2015	2015–2016	2016–2017	2017–2018	2018–2019	2019–2020	2020–2021	2021–2022
Percentage of clients who used OGS products within the past 12 months?	85%	94%	91%	89%	90%	89%	86%	93%
Overall satisfaction with the quality of OGS products	n/a	n/a	91%	97%	89%	95%	94%	88%
Percentage of clients who used OGS products to make a decision	90%	91%	78%	77%	77%	71%	74%	83% [1]
Did OGS products allow clients to focus their efforts on areas of higher potential and/or interest?	83%	58%	83%	57%	64%	66%	63%	71% [2]
Did OGS products reduce the time and cost to advance to the next stage of exploration or decision making?	83%	58%	56%	60%	55%	54%	66%	58% [2]
Did the use of OGS products improve clients' exploration models or strategies?	80%	58%	50%	69%	64%	86%	77%	71% [3]
Did the use of OGS products reduce clients' decision risks?	78%	36%	50%	60%	34%	36%	42%	37% [3]
Did the use of OGS products/services provide evidence of the presence or absence of critical features, target deposit type or topic of interest?	83%	53%	64%	74%	45%	52%	45%	53% [3]

[1] An open-ended question asking respondents if there was a specific reason why they did not use OGS products to make a decision. Mineral/resource/exploration clients: 29% had no specific reason why; 29% said the COVID-19 pandemic was a factor. Land-use/groundwater/environmental clients: 29% had no specific reason why; 29% said the COVID-19 pandemic was a factor.
[2] Option for respondents to select "Other" where they could provide further comments on how products increased the efficiency of their decision-making: 12% of mineral/resource/exploration clients and 18% of land-use clients responded.
[3] Option for respondents to select "Other" where they could provide further comments on how products increased the effectiveness of their decision-making: 11% of mineral/resource/exploration clients and 13% of land-use clients responded.
n/a = no data available.

Table 2.4. Ontario Geological Survey 2021–2022 client survey questions and summary of results for OGS service users.

Survey Question	Mineral / Resource / Exploration							
	2014–2015	2015–2016	2016–2017	2017–2018	2018–2019	2019–2020	2020–2021	2021–2022
Percentage of clients who used OGS services within the past 12 months?	n/a	n/a	96%	85%	53%	54%	42%	44%
Overall satisfaction with the quality of OGS services	n/a	n/a	91%	82%	84%	81%	80%	85%
Percentage of clients who used OGS services to make a decision	69%	80%	68%	54%	48%	32%	35%	46% [4]
Did OGS services allow clients to focus their efforts on areas of potential and/or interest?	74%	76%	73%	50%	50%	75%	76%	71% [5]
Did OGS services reduce the time and cost to advance to the next stage of exploration or decision making?	61%	65%	50%	38%	32%	34%	33%	39% [5]
Did the use of OGS services improve clients' exploration models or strategies?	80%	76%	55%	46%	46%	56%	53%	53% [6]
Did the use of OGS services reduce clients' decision risks?	74%	65%	60%	39%	25%	32%	32%	40% [6]
Did the use of OGS services provide evidence of the presence or absence of critical features, target deposit type or topic of interest?	72%	57%	59%	41%	37%	50%	41%	38% [6]

Table 2.4, *continued*.

Survey Question	Land-Use Planning / Groundwater / Environmental							
	2014–2015	**2015–2016**	**2016–2017**	**2017–2018**	**2018–2019**	**2019–2020**	**2020–2021**	**2021–2022**
Percentage of clients who used OGS services within the past 12 months?	n/a	n/a	100%	97%	75%	68%	48%	39%
Overall satisfaction with the quality of OGS services	n/a	n/a	91%	97%	87%	100%	89%	100%
Percentage of clients who used OGS services to make a decision	90%	91%	78%	77%	77%	74%	47%	86% [4]
Did OGS services allow clients to focus their efforts on areas of potential and/or interest?	83%	58%	83%	57%	67%	90%	58%	73% [5]
Did OGS services reduce the time and cost to advance to the next stage of exploration or decision making?	83%	58%	56%	60%	56%	52%	75%	60% [5]
Did the use of OGS services improve clients' exploration models or strategies?	80%	58%	50%	69%	59%	83%	75%	71% [6]
Did the use of OGS services reduce clients' decision risks?	78%	36%	50%	60%	23%	40%	44%	29% [6]
Did the use of OGS services provide evidence of the presence or absence of critical features, target deposit type or topic of interest?	83%	53%	64%	74%	44%	50%	56%	43% [6]

[4] An open-ended question was asked to respondents if there was a specific reason why they did not use OGS services to make a decision. Mineral/resource/exploration clients: 30% had no specific reason why; 10% said the COVID-19 pandemic was a factor. Land-use/groundwater/environmental clients: 50% had no specific reason why.

[5] Option for respondents to select "Other" where they could provide further comments on how services increased the efficiency of their decision-making: 13% of mineral/resource/exploration clients and 13% of land-use clients responded.

[6] Option for respondents to select "Other" where they could provide further comments on how services increased the effectiveness of their decision-making: 14% of mineral/resource/exploration clients and 7% of land-use clients responded.

n/a = no data available.

SUCCESSES WITH PRODUCTS AND SERVICES

The OGS measures its success with products and services by monitoring exploration companies working in Ontario who reference OGS data to make an informed decision. The 6 most recent successes are described below.

1. In January 2022, Green Technology Metals increased its claim holdings in northwestern Ontario from 9467 ha to 35 576 ha. This includes expansion to the company's existing projects through pegging (Seymour and Root); acquisition of a package comprising 31 claims for other project areas through an optioned agreement with Solstice Gold Corp. (Pennock Lake, Superb Lake, Root Bay and Gathering Lake); and acquisition of the new Allison lithium project at the Allison Lake batholith. The company news release described the acquisition as the "Allison Lake batholith represents an important new exploration target" citing and crediting an OGS publication (Breaks, Selway and Tindle 2003). The news release also credits multiple other publications by the OGS as support for their decision to expand their lithium footprint. (Green Technology Metals, news release, January 24, 2022)

2. Solstice Gold Corp. acquired the 23 km^2 New Frontier gold project in January 2022 and announced the expansion of their RLX gold project from 5.5 km^2 to 11 km^2; both projects are located north of Red Lake. Solstice credits the OGS' *Recommendations for Exploration 2020-2021* (Lewis 2021) and mapping of Nungesser Lake completed by the OGS in 1990 (Stone and Good 1990) in their news releases. In addition, in May 2022, Solstice staked mining claims totalling 17.1 km^2 to form the Lightspeed lithium project, located northwest of Thunder Bay,

based on a map published by the OGS (Sage et al. 1974) and subsequent lake sediment sampling by the OGS in 2003 (Jackson 2003).
(Solstice Gold Corp., news releases, January 10, March 14, May 31 and June 21, 2022)

3. In February 2022, Musk Metals Corp. acquired the Allison Lake east lithium claims spanning over 1500 ha, located east of Red Lake within the Allison Lake batholith, crediting an OGS publication (Breaks, Selway and Tindle 2003).
(Musk Metals, news release, February 1, 2022)

4. In February 2022, McFarlane Lake Mining Ltd. acquired, through purchase from Transition Metals Corp., the Mongowin property that comprises 122 claims, totalling 2605 ha, located east of Sudbury. In the news release, McFarlane Lake credits the OGS for identifying—as a "top gold exploration opportunity"—the region in which its 2 properties west of Sudbury are located.
(McFarlane Lake Mining, news release, February 1, 2022)

5. On the day of release of the *2021–2022 Recommendations for Exploration* published by the OGS, the Bedivere Lake–Lac des Mille Lacs area lithium property was staked by a local prospector who had participated in the OGS Prospector Course given by the Thunder Bay Resident Geologist Office less than a year prior (May to August 2021). In April 2022, International Lithium Corp. optioned this property, now known as the Wolf Ridge property, comprising 275 claims (~5700 ha), located northwest of Thunder Bay, and cites excerpts and a map from the OGS' *Recommendations for Exploration* by Campbell (2022) in their news release.
(International Lithium Corp., news release, April 25, 2022)

6. In May 2022, Portofino Resources Inc. acquired 3 claims adding to its Allison Lake north project now comprising 7 claims, totalling 2286 ha, located east of Red Lake. The news release credits an OGS publication (Breaks, Selway and Tindle 2003).
(Portofino Resources Inc., news release, May 10, 2022)

SUCCESSES WITH INDIGENOUS COMMUNITIES

The OGS measures its success with Indigenous communities through qualitative data collection (e.g., collaborations, blessings, testimonials). In 2022, the OGS collaborated with many Indigenous communities, gave 15 presentations to communities, held 2 days of field mapping with local community members, and were invited to host a booth at 2 major community events. The following successes were documented (*see also* Levesque and Bennett, this volume, Article 3).

1. In February and March of 2022, staff of the Resident Geologist Program gave 2 "Introductory Critical Minerals" presentations and an online demonstration of the Ontario Mineral Inventory (OMI) database as part of the Mineral Development Advisor and Community Consultation Liaison Officer Training Sessions.

2. Between January and July of 2022, the Indigenous Geoscience Liaisons gave 3 overview presentations about OGS products and services to Sheshegwaning First Nation, Algonquins of Ontario, and to the new Mineral Development Advisors of Sagamok and Michipicoten First Nations.

3. Throughout May and June of 2022, the Indigenous Geoscience Liaisons and staff of the Earth Resources and Geoscience Mapping Section gave 10 presentations to various communities about the mapping projects located on their traditional land use area (Brunswick House First Nation, Michipicoten First Nation, Missanabie Cree First Nation, Red Sky Métis Independent Nation, Mushkegowuk Tribal Council, Mohawks of the Bay of Quinte, Naicatchewenin First Nation, Chapleau Cree First Nation, Mississaugas of the Credit First Nation, and Algonquins of

Ontario). These project presentations were extremely well received, leading to further collaborations and endorsement from the communities for OGS projects and invitations to community events.

4. In May 2022, Missanabie Cree First Nation granted a Band Council Resolution to the OGS that allowed mapping to proceed on their traditional land use area and federal reserve lands (Project NE-22-002; *see also* Vice, Perrouty and Robichaud, this volume, Article 8). OGS staff were also invited to host a booth at the Missanabie Annual Community Gathering held on August 15–16, 2022.
5. On June 23, 2022, the Mineral Development Advisor for Michipicoten First Nation accompanied the Indigenous Geoscience Liaisons, Lianna Vice and crew for a day of field mapping sensitive areas on Dog Lake (Project NE-18-007; *see also* Vice, this volume, Article 7). The Indigenous Geoscience Liaisons and staff of the Resident Geologists Program were also invited to host a booth at the Michipicoten Youth and Elder Annual Gathering on July 28, 2022.
6. Staff and managers from the Earth Resources and Geoscience Mapping Section and the Director's Office (Project SO-19-001; *see also* Hastie, MacDonald and Duguet, this volume, Article 14) received a traditional knowledge keeper blessing on June 13, 2022, from Mississaugi First Nation, as well as a closing ceremony including a field excursion on August 10, 2022. A community member also joined the crew throughout the field season to share traditional knowledge of the land and geoscience information.
7. On August 9, 2022, Lands and Resource staff of Chapleau Cree First Nation accompanied the Indigenous Geoscience Liaisons, Thomas Gemmell and crew for a day of field mapping (Project NE-22-003; *see also* Gemmell and Buyers, this volume, Article 6).

NEXT STEPS

The OGS will continue to

- collect performance measures data that include baseline values, target values and actual values;
- take steps to address gaps and downward trends and to continually improve products and services;
- communicate the value and relevance of public geoscience information;
- improve the integration of geoscience information into broader government and public decision-making; and
- build strong and successful collaborations and relationships with Indigenous communities.

REFERENCES

Breaks, F.W., Selway, J.B. and Tindle, A.G. 2003. Fertile peraluminous granites and related rare-element mineralization in pegmatites, Superior Province, northwest and northeast Ontario: Operation Treasure Hunt; Ontario Geological Survey, Open File Report 6099, 179p.

Campbell, D.A. 2022. Lithium potential in the Bedivere–Lac des Mille Lacs lakes area; *in* Ontario Geological Survey, Resident Geologist Program, Recommendations for Exploration 2021–2022, p.54-58.

Jackson, J.E. 2003. Lake sediment geochemical data from the Ignace survey area, northwestern Ontario: Operation Treasure Hunt; Ontario Geological Survey, Miscellaneous Release—Data 118.

Lewis, S.O. 2021. Deep tapping seismic structure in the Red Lake district; *in* Ontario Geological Survey, Resident Geologist Program, Recommendations for Exploration 2020–2021, p.9-13.

Sage, R.P., Breaks, F.W., Stott, G.M., McWilliams, G.M. and Atkinson, S. 1974. Operation Ignace–Armstrong, Ignace–Graham sheet, districts of Thunder Bay, Kenora and Rainy River; Ontario Division of Mines, Preliminary Map P.964, scale 1:126 720.

Stone, D. and Good, D.J. 1990. Precambrian geology, Nungesser Lake; Ontario Geological Survey, Preliminary Map P.3175, scale 1:50 000.

3. Activities of the Indigenous Geoscience Liaisons in 2021–2022



M.D. Levesque[1] and D.J. Bennett[1]

[1]Director's Office, Ontario Geological Survey

INTRODUCTION

The Ontario Geological Survey (OGS) is committed to building meaningful, collaborative and long-term relationships with Indigenous communities for anticipated and ongoing geoscience project areas. One of the current OGS mandates is to "encourage and facilitate Indigenous participation in Ontario's economy in a way that recognizes and is respectful of Indigenous rights and culture" and our work within Indigenous communities aims to meet and exceed this mandate. Since 2016, the OGS Indigenous Geoscience Liaisons (IGL) have been focussed on engaging, building and maintaining strong, respectful treaty relationships with First Nations and Métis communities across Ontario that have measurable and realistic outcomes. One of the key responsibilities of the IGL position is to engage with our treaty partners in co-development, co-design and implementation of geoscience projects and to discuss application and potential impacts of OGS geoscience project work and results. Additionally, we function as pivotal liaisons, hearing the directions and priorities of First Nations and Métis communities and translating those priorities to ministry employees to ensure projects and participation is developed and facilitated in a way that is appropriate to each individual community. The diminishing restrictions associated with the COVID-19 pandemic allowed 17 OGS projects to move forward in the summer and fall of 2022. As a result of these projects, over 45 individual Indigenous communities were consulted. The following article outlines some of these key interactions, with timelines, results and future objectives.

INDIGENOUS ENGAGEMENT BY THE INDIGENOUS GEOSCIENCE LIAISONS

Table 3.1. Indigenous Community engagements by the Indigenous Geoscience Liaisons.

Community	Visit	Purpose and Outcome
Moose Cree First Nation	September 22, 2021	*Purpose:* Issued letter detailing geophysics project in their traditional land use area. *Outcome:* Project on temporary hold.
Fort William First Nation	October 15, 2021	*Purpose:* Request for local flint for Elder ceremonial use. *Outcome:* Resident Geologist Program and IGL staff collected and delivered local flint samples along with maps of locations where local flint can be found.
Taykwa Tagamou First Nation	November 8, 2021	*Purpose:* Issued letter detailing geophysics project in their traditional land use area. *Outcome:* Project on temporary hold.

Summary of Field Work and Other Activities, 2022,
Ontario Geological Survey, Open File Report 6390, p.3-1 to 3-6.

© King's Printer for Ontario, 2022

Table 3.1, *continued*.

Community	Visit	Purpose and Outcome
Anishinabek Nation Northern Superior Regional Table	January 11, 2022	*Purpose:* Meeting focussed on geographic information system values mapping and mine rehabilitation. *Outcome:* Attended to answer OGS related questions. Continued relationship building and engagement.
Anishinabek Nation Lake Huron Regional Table	January 18, 2022	*Purpose:* Meeting focussed on values mapping and mine rehabilitation. *Outcome:* Attended to answer OGS related questions. Continued relationship building and engagement.
Sheshegwaning First Nation	January 20, 2022	*Purpose:* Provided OGS products and services presentation to Community Staff member. *Outcome:* Introduction to the OGS. IGL follow up with OGS maps and resources. Possible future engagement.
Anishinabek Nation Southeast and Southwest Regional Table	January 25, 2022	*Purpose:* Meeting focussed on values mapping and mine rehabilitation. *Outcome:* Attended to answer OGS related questions. Continued relationship building and engagement.
Northeast Mineral Development Advisor and Community Consultation Liaison Officer Training	February 7, 2022	*Purpose:* Introductory "Critical Minerals" presentation was given by the Resident Geologist Program staff. *Outcome:* Trainees enjoyed the presentation and generated good discussion.
Northwest Mineral Development Advisor and Community Consultation Liaison Officer Training	March 3, 2022	*Purpose:* Introductory "Critical Minerals" presentation was given by the Resident Geologist Program staff. *Outcome:* Trainees enjoyed the presentation and generated good discussion.
Southern Mineral Development Advisor and Community Consultation Liaison Officer Training	March 9, 2022	*Purpose:* Resident Geologist Program staff presented Ontario Mineral Inventory (OMI) database and online tutorial. *Outcome:* Trainees enjoyed the presentation and generated good discussion.
Mineral Development Advisor orientation and training	April 26, 2022	*Purpose:* OGS products and services presented to new Sagamok and Michipicoten Mineral Development Advisors. *Outcome:* Trainees enjoyed the presentation and generated good discussion. IGL followed up with OGS maps and links.
Informal proposed mapping projects notification letter	April–May, 2022	*Purpose:* Informal emails were sent out for 13 Earth Resources and Geoscience Mapping Section mapping projects. OGS contacted over 45 Indigenous communities notifying them of proposed project(s) in their traditional land use area and offering a presentation. *Outcome:* OGS formally presented to 9 Indigenous communities along with 6 informal conversations sharing information about Earth Resources and Geoscience Mapping Section mapping projects. Positive feedback with no opposition to our geoscience projects.
Brunswick House First Nation	May 4, 2022	*Purpose:* Earth Resources and Geoscience Mapping Section presentation regarding proposed mapping project in their traditional land use area. *Outcomes:* Supportive of project. IGL followed up with OGS maps and resources.
Michipicoten First Nation	May 9, 2022	*Purpose:* Earth Resources and Geoscience Mapping Section presentation regarding proposed mapping project in their traditional land use area. *Outcomes:* Sensitive areas on Dog Lake needed community member present while mapping. Earth Resources and Geoscience Mapping Section was provided a list of features to look for while mapping. IGL followed up with OGS maps and resources.
Missanabie Cree First Nation	May 9, 2022	*Purpose:* Earth Resources and Geoscience Mapping Section presentation regarding proposed mapping project in their traditional land use area. *Outcomes:* Obtained Band Council Resolution (BCR) to map their traditional land use area and federal reserve lands, as well as an invite to their annual gathering to set up booth and share geoscience information. IGL followed up with OGS maps and links.

Table 3.1, *continued*.

Community	Visit	Purpose and Outcome
Mohawks of the Bay of Quinte	May 11, 2022	*Purpose:* Initial meeting to introduce OGS to community staff members. *Outcome:* Introduced to community contact for all future OGS engagement and notifications. Follow up mapping presentation will be provided.
Red Sky Métis Independent Nation	May 16, 2022	*Purpose:* Earth Resources and Geoscience Mapping Section introduced OGS mapping projects in their traditional land use area. *Outcomes:* Good discussion, supportive of project and would like to receive periodic updates. IGL followed up with OGS maps and resources.
Mushkegowuk Tribal Council	May 19, 2022	*Purpose:* Presented 3 proposed Earth Resources and Geoscience Mapping Section mapping projects to Mushkegowuk Mineral Development Advisor. *Outcome:* Good discussion and supportive of projects. IGL followed up with OGS maps and resources.
Mohawks of the Bay of Quinte	May 25, 2022	*Purpose:* Provided Earth Resources and Geoscience Mapping Section mapping presentation as a follow up to the OGS introduction. *Outcome:* Community interested in possible events when mapping on or near their federal reserve land next year. IGL followed up with OGS maps and resources.
Naicatchewenin First Nation	May 27, 2022	*Purpose:* Earth Resources and Geoscience Mapping Section presented proposed mapping project to Business Development Advisor. *Outcome:* Community wants to get involved, especially the youth. IGLs followed up with OGS maps and resources.
Formal proposed mapping projects notification letters	June 2022	*Purpose:* Formal notifications were emailed and mailed for 13 Earth Resources and Geoscience Mapping Section mapping projects. OGS contacted over 45 Indigenous communities notifying them of proposed projects in their traditional land use area and offering a presentation. *Outcome:* OGS presented to 9 individual Indigenous communities sharing information about Earth Resources and Geoscience Mapping Section mapping projects in their traditional land use area along with 6 informal conversations. No project opposition received.
Chapleau Cree First Nation	June 9, 2022	*Purpose:* IGL presented 2 proposed Earth Resources and Geoscience Mapping Section mapping projects. *Outcomes:* Lands and Resources staff member requested to join and OGS geoscientist for a day of mapping. IGL followed up with OGS maps and resources.
Mississaugi First Nation	June 13, 2022	*Purpose:* Opening blessing for Earth Resources and Geoscience Mapping Section mapping project with community traditional knowledge keeper. Evening meeting with Lands and Resources council to share geoscience information regarding the mapping project. *Outcomes:* Generated great discussion during evening meeting about the significance of rocks in their area and how future eco tourism opportunities may exists.
Michipicoten First Nation	June 23, 2022	*Purpose:* Day of mapping sensitive areas on Dog Lake with Michipicoten Mineral Development Advisor. *Outcomes:* Great collaboration, sensitive areas were mapped and sampled with oversight and approval of Mineral Development Advisor.
Algonquins of Ontario	July 7, 2022	*Purpose:* Introductory OGS products and services presented to planning and environment working group. *Outcomes*: Possible future engagement and mapping proposal for surficial mapping of their traditional land use area which has never been mapped.
Mohawks of Akwesasne	July 14, 2022	*Purpose:* Informal conversation with Grand Chief. *Outcomes:* Appreciates the notification and information sharing. Supportive of our projects.
Michipicoten First Nation	July 28, 2022	*Purpose:* IGL and Resident Geologist Program displayed "Minerals in our lives" and panning for gemstones at Youth and Elder annual gathering. *Outcomes:* Great interactions with community members. Invited back for next year's event.

Table 3.1, *continued*.

Community	Visit	Purpose and Outcome
Chapleau Cree First Nation	August 9, 2022	*Purpose:* Chapleau Cree Lands and Resources staff joined Earth Resources and Geoscience Mapping Section geoscientist and IGL for a day of mapping. *Outcomes:* Great discussion and interaction. Possible day of mapping with youth Lands and Resources group next year.
Mississaugi First Nation	August 10, 2022	*Purpose:* Closing ceremonies and events for Earth Resources and Geoscience Mapping Section mapping project. *Outcomes:* Opening and closing ceremony by community traditional knowledge keeper. Field tours of local outcrop. Earth Resources and Geoscience Mapping Section mapping presentation.
Missanabie Cree First Nation	August 15–16, 2022	*Purpose:* Attended annual Community gathering. Day 1 – "Minerals in our lives", panning for gems with children, rock walk with adults. Day 2 – Focussed on critical minerals. *Outcomes:* Large community event with hundreds of community members attending. Numerous positive interactions.

FIRST NATION BEST PRACTICES DOCUMENT

The IGLs have prepared a First Nations Best Practices Guide that has been shared internally with OGS staff and will also be provided to new OGS staff during onboarding. The Indigenous Consultation and Partnership Branch (ICPB) assisted in the review of this guide. This introductory guide provides staff with the base knowledge of best practices when interacting or visiting a First Nation community and resources for self-learning. Document was released to staff and utilized for onboarding new staff and students for the summer 2022 field season.

MONTHLY INDIGENOUS LEARNING ACTIVITIES

During monthly OGS section staff meetings, the IGLs have been presenting Indigenous learning activities. Presentations have covered topics such as

- Introductions to Indigenous groups across Ontario
- Woodland art
- Cultural appropriation
- Indigenous literature
- Colonization

These short presentations and/or activities help introduce staff to various Indigenous topics and aim to promote awareness of different cultures and increase inclusivity. These 15-minute monthly presentations are enjoyed by staff, and IGLs often receive positive feedback and follow-up conversations on each respective topic. During each session, staff are encouraged to do their own follow-up research, contact IGLs for more information and resources and participate in one of the learning activities. These activities are set to continue in the fall and winter of 2022–2023.

WOODLAND ART PRESENTATIONS

Throughout the year, the IGL has given presentations on Indigenous woodland art to both internal and external audiences. Externally, the presentation has been provided to the Rainbow District School Board (Sudbury) for the second year. The presentation is focussed on introducing woodland art and demonstrating the multiple ways of interpreting Indigenous art. Woodland art is used as an avenue to share Indigenous history and customs and explain why the IGL role is essential to the success of the OGS.

INFORMAL NOTIFICATIONS AND VIRTUAL PRESENTATIONS

For the 2022 field season, a new form of communication was piloted for communities with mapping projects being proposed on their traditional land use area (TLUA). This communication method, termed "informal notifications", involved scoping in impacted communities and issuing an email to share with them the proposed geoscience project in their TLUA and to give them points of contact should they want further information. These informal notifications provided communities advanced notice of proposed projects and offered an opportunity for them to provide input, ask questions, or request specific information about the proposed project before the field season commenced. This initiative was highly successful, resulting in numerous phone calls with individual Indigenous communities to explain who we are, what we do and what the community-specific project entails. Some conversations led to more detailed presentations.

Requested presentations were delivered by Earth Resources and Geoscience Mapping Section and IGL staff to Chiefs and Councils, Lands and Resources departments, and Mineral Development Advisors. Presentations were immensely successful and led to invitations to community events across Ontario. We would like to extend a thank you to all staff members for successfully working through this new process while also preparing for the field season in record time!

MICHIPICOTEN FIRST NATION YOUTH AND ELDER EVENT

Our staff was invited to the Michipicoten First Nation's youth and elder event, which was held in the community during the last week of July. Four staff members attended the event, including 2 summer students. A booth was set up on the event grounds featuring "Minerals in our lives" which emphasized critical minerals, a fossils of Ontario display, and a children's dig for stones activity. We also provided copies of "An Introduction to Ontario's Critical Minerals", the OGS placemat along with 2 Indigenous language translations, and the fossils of Ontario poster. There were many great discussions with community members from across the province about geology, mapping and critical minerals.

MISSANABIE CREE ANNUAL GATHERING

As a result of mapping and information-sharing presentations, Missanabie Cree First Nation provided the OGS with a Band Council Resolution allowing the OGS to map their federal reserve lands and an invitation to their annual gathering. The OGS attended the annual gathering over 2 days. On the first day, the OGS set up a booth containing "Mineral in our lives" display, OGS products, such as the OGS placemat and "An Introduction to Ontario's Critical Minerals" publication, along with other resources. We also co-ordinated several events for attendees, such as a gem panning activity for youth and a rock walk with the adults where information was shared about the rocks found in the Missanabie Cree traditional land use area. Staff from across the OGS were involved in each aspect of the activities, with Earth Resources and Geoscience Mapping Section staff and students staffing the booth, identifying rocks, and leading a short field excursion for the community. Resident Geologist Program staff also attended and provided knowledge regarding exploration activity in the area. In addition to the previous activities, we were honoured to collaborate with Missanabie Cree experts in a water talk and testing event for community members. This activity involved a quick discussion about water quality and then taking interested community members down to the beach to do live testing, talk about the chemistry of the tests and discuss the meaning of the results. The water testing event was assisted by the Water Rangers organization, based in Toronto; they provided the testing materials. The second afternoon was focussed on critical minerals, with displays and information sharing. Both days led to numerous positive interactions with community members.

MISSISSAUGI FIRST NATION COLLABORATION WITH OGS MAPPING PROJECT

Mississaugi First Nation and the OGS have worked on a collaborative project since 2018. The mapping was nearly complete, with 1 final field season remaining in 2020, when the pandemic restrictions hit and prevented OGS geoscientists from completing the mapping project. The geoscience mapping crew returned to the area in 2022 to complete the final year of mapping.

To open the mapping activity, Mississaugi First Nation invited the OGS to participate in an opening ceremony to start the project off well and ensure the success of the mapping and the partnership. Staff and managers from Earth Resources and Geoscience Mapping Section and the Director's Office attended the event, along with some band council members, and Mississaugi First Nation Lands and Resources staff. After the ceremony, some community staff along with a traditional knowledge keeper and the OGS staff shared stories and hopes for the community's future regarding geology. Project Lead Evan Hastie presented information to all the Mississaugi First Nation Lands and Resources staff regarding the final year of mapping, what had been done to date and what were the expected outcomes of the project. Collaboration involved a community member joining the crew in the field to share traditional knowledge of the land and receive teachings about geology and mapping. The closing ceremony involved staff from Earth Resources and Geoscience Mapping Section, the Director's Office and the Resident Geologist Program, as well as band council members, Lands and Resources staff, and community members. The event included a short field excursion to visit an outcrop and speak about the rocks and geology in the area. Collaborating on this mapping project with Mississaugi First Nation has been a great success.

This page left blank intentionally

Earth Resources and Geoscience Mapping Section

4. Earth Resources and Geoscience Mapping Section: 2022–2023 Program and Projects Overview



J.H. Hechler[1], R.M. Easton[1], S. Préfontaine[1], M. Duguet[1], L. Robichaud[1] and R. Cormier[1]

[1]Earth Resources and Geoscience Mapping Section, Ontario Geological Survey

GOAL AND RESPONSIBILITY OF THE SECTION

The goal of the Ontario Geological Survey's (OGS) Earth Resources and Geoscience Mapping Section (ERGMS) is to improve the understanding of the geology, geochemistry and Earth resources of the province and to convey this knowledge to the public through multi-year, multi-disciplinary geoscience projects that address key geoscience problems. These studies may be delivered as part of the ERGMS geoscience mapping function or through collaborative geoscience projects or initiatives.

The ERGMS is responsible for

- mapping Ontario's Precambrian and Phanerozoic bedrock geology and assessing its inherent resources at a regional scale;
- mapping and sampling of Quaternary sediments for the purpose of mineral resource assessment, land-use planning, aggregate delineation, geotechnical applications, etc.;
- three-dimensional (3-D) mapping of Quaternary and Phanerozoic hydrostratigraphic units and their contained groundwater resources at a regional scale; determining the relationship between aquifer composition and regional groundwater geochemistry;
- collecting regional ground and airborne geophysical data and producing derivative products in support of bedrock geology and groundwater mapping projects, mineral exploration and land-use planning;
- collecting regional surficial geochemistry data from water and other surficial media (e.g., lake and stream sediments, peat, etc.) to support mineral exploration, mapping of bedrock and sediments, land-use planning, assessment of watershed quality and the establishment of natural baseline databases;
- mapping aggregate and industrial minerals to provide up-to-date inventories and quality assessments of potential aggregate and industrial mineral resources; and
- mapping bedrock that hosts traditional and unconventional non-renewable energy resources to identify new energy sources and better understand the effect of hydrocarbon interaction on groundwater resources.

The program direction and strategies of the ERGMS address the strategic objectives and core business of the Ontario Geological Survey Branch, which, in turn, are linked to those of the Mines and Minerals Division of the Ministry of Mines (Ministry of Northern Development, Mines, Natural Resources and Forestry prior to June 2022). Ministry and Government priorities are achieved through specific ERGMS strategies and initiatives that consist of one or more projects. Staff of the OGS conducts an annual, project

Summary of Field Work and Other Activities, 2022,
Ontario Geological Survey, Open File Report 6390, p.4-1 to 4-18.

© King's Printer for Ontario, 2022

planning exercise, including project proposals development, evaluation and selection. This project planning exercise is designed to achieve alignment of individual projects with higher level Divisional, Ministry and Government priorities. This article reports on the current activities of the ERGMS.

The COVID-19 pandemic has had widespread impacts in these past 3 years. In Ontario, the provincial government implemented a work from home directive shortly after March 17, 2020. The ongoing impacts of the pandemic necessitated the cancellation of the Ontario Geological Survey's 2020 summer field season, and significantly restricted the 2021 summer field season. The 2022 summer field season, although somewhat impacted, was the first fulsome return to field work with 13 field crews deployed across Ontario. Additionally, the 2022 transition from remote work to office for many occurred relatively smoothly, with staff returning to the office workplace a minimum of 3 days per week and working remotely when not in the office.

The ERGMS supported 72 active projects during the 2022–2023 fiscal year, which includes 55 active core projects and 17 active collaborative projects (Table 4.1). The collaborative projects include 1 project with other provincial ministries; 1 project with the City of Ottawa; 1 project in collaboration with the Mineral Exploration Research Centre (MERC) at Laurentian University, Metal Earth and the Royal Ontario Museum (ROM); and 15 graduate thesis projects with universities. Locations of projects for which there are corresponding articles in this volume are depicted in Figure 4.1.

From December 2021 to December 2022, inclusive, the ERGMS produced 4 Open File Reports, 3 Miscellaneous Releases—Data (MRD), and 1 Groundwater Resources Study (*see* "List of Publications" in this article for a complete listing of these publications). The ERGMS has several online databases: some of the more recent ones include the Aggregate Resources of Ontario compilation, the Lake Geochemistry of Ontario compilation, and the Geochronology Inventory of Ontario, which are available for download through GeologyOntario (www.geologyontario.mndm.gov.on.ca/index.html) and for viewing in the Google Earth™ mapping service by downloading the appropriate *.kml* file through the OGSEarth Web site (www.geologyontario.mndm.gov.on.ca/ogsearth.html). The ERGMS staff presented several technical talks and posters at various geoscience forums and meetings, including virtual geoscience meetings, throughout the year.

ERGMS STRATEGIES AND OBJECTIVES

The Earth Resources and Geoscience Mapping Section (ERGMS) strategies and objectives are derived from OGS strategic priorities, which stem from the Mines and Minerals Division Strategic Framework and Ministry business goals.

The purpose of ERGMS strategies and objectives is to focus staff and resources in key geological areas or geoscience themes, over a period of 3 to 5 years, to contribute to

- expanding the geoscience database of Ontario;
- supporting sustainable development and effective land-use planning;
- providing the geoscience framework for groundwater use and source water protection, public health and safety and the public good; and
- supporting and attracting new mineral investment.

To successfully deliver these strategies, the ERGMS is fully engaged in building new and strengthening existing collaborations with Indigenous communities, the private sector, academia, federal agencies and other provincial ministries on initiatives of mutual interest.

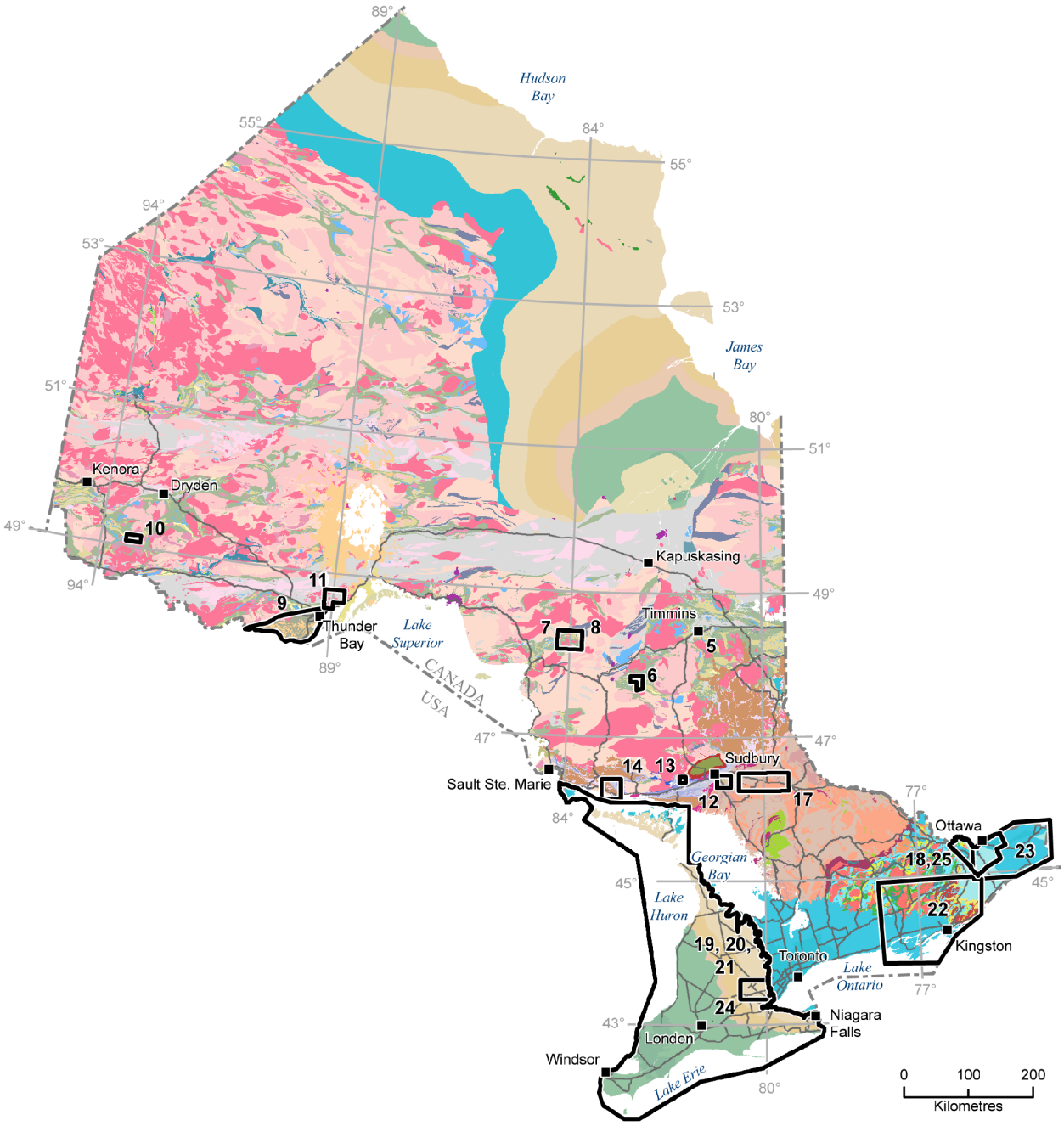


Figure 4.1. Locations of the Earth Resources and Geoscience Mapping Section projects in Ontario as described in *Summary of Field Work and Other Activities, 2022.* Numbers correspond to article numbers; note articles 15 and 16 are provincial in scope and are not indicated on the figure. Bedrock geology *from* Ontario Geological Survey (2011).

Table 4.1. Earth Resources and Geoscience Mapping Section collaborative initiatives and projects, 2022–2023.

Initiative	Project	ERGMS Core Program / Project Collaborator(s)	Project Progress
Geophysical Techniques in Support of Bedrock Geology Mapping Initiative	Airborne gravity and magnetic surveys over the Hornepayne and Manitouwadge areas north central Ontario ▸ Reprocessing and/or reformatting of donated survey data	ERGMS Core Program (data sets donated by Nuclear Waste Management Organization)	Ongoing – Geophysical Data Sets and maps in progress
	Airborne geophysical surveys, request for data ▸ Purchase of geophysical data from exploration companies for public release	ERGMS Core Program	Request issued in fall 2022
Far North Land Use Planning Initiative	Bedrock geological compilation of the Obabigan–Neawagank lakes area, North Caribou greenstone belt ▸ 1:50 000 scale	ERGMS Core Program	New project – compilation in progress
	Bedrock geological compilation of the Opapimiskan Lake area, North Caribou greenstone belt ▸ 1:50 000 scale	ERGMS Core Program	New project – compilation in progress
	Bedrock geological compilation of the North Caribou–Wachusk lakes area, North Caribou greenstone belt	ERGMS Core Program	Completed ▸ Summary *of Field Work* article in 2021 ▸ Preliminary Map submitted in 2022 for publication
	Far North terrain mapping project ▸ remote predictive mapping, field checking; Quaternary mapping ▸ Sandy Lake area ▸ Pickle Lake–Cat Lake area	ERGMS Core Program	Ongoing – Predictive Quaternary geology mapping in the Sandy Lake area in 2018, preliminary maps in progress ▸ *Summary of Field Work* articles published in 2017, 2018 Ongoing –Predictive Quaternary geology mapping in the Pickle Lake–Cat Lake area in 2019 ▸ *Summary of Field Work* articles published in 2019, 2020
Surficial Geochemistry of Northern Ontario Initiative	Marathon region sediment and water sampling project high-density lake sediment and water geochemistry survey	ERGMS Core Program	Ongoing – MRD in progress
	Biogeochemical and electrical investigations in soils over a forest ring ▸ Thorn North forest ring	ERGMS Core Program University of Alberta, University of Toronto	Ongoing – field work completed, analyses in progress ▸ *Summary of Field Work* articles published in 2018, 2019 ▸ Journal paper: von Gunten et al. (2018)
	Surficial geochemistry sampling over the Borden Lake area and Kapuskasing Structural Zone	ERGMS Core Program (internship project: L.M. Colgrove)	Ongoing – OFRs and MRDs in preparation ▸ *Summary of Field Work* article published in 2016
Surficial Mapping of Northern Ontario Initiative	Highway 17 mapping and sampling initiative	ERGMS Core Program	New project – mapping and sampling began in September 2021 and continued in 2022

Abbreviations: *MRD, Miscellaneous Release—Data; OFR, Open File Report; GDS, Geophysical Data Set.*

Table 4.1, *continued.*

Initiative	Project	ERGMS Core Program / Project Collaborator(s)	Project Progress
Proterozoic Initiative	Hyman Township bedrock geology mapping project ▸ 1:20 000 scale bedrock geology mapping	ERGMS Core Program	New project – mapping in 2022 ▸ *Summary of Field Work* (this volume, Article 13)
	Southwest Sudbury Structure bedrock geology mapping project ▸ 1:20 000 scale bedrock geology mapping	ERGMS Core Program	Ongoing – bedrock geology mapping in Denison Township in 2018; field work for Drury Township completed ▸ *Summary of Field Work* articles published in 2016, 2017, 2018 ▸ Preliminary Map, OFR and MRD for Drury Township published in 2018
	Structural, metamorphic and lithologic controls on low-sulphide PGE mineralization, Denison and Drury townships	PhD thesis (C-A. Généreux) Laurentian University	Ongoing – field work completed, thesis writing in progress ▸ *Summary of Field Work* articles published in 2016, 2017 ▸ Journal paper: Généreux, Tinkham and Lafrance (2021)
	Geology and mineral potential of the Grenville Front tectonic zone near Sudbury ▸ 1:50 000 scale bedrock geology mapping	ERGMS Core Program	Ongoing – field work in 2021 and 2022, analyses in progress ▸ *Summary of Field Work* (this volume, Article 12) ▸ Field trip guidebook: Easton (2022c)
	Proterozoic mafic intrusions of the Sudbury area ▸ Compilation and characterization project	ERGMS Core Program	Ongoing – compilation and database construction begun
	Compilation and reconnaissance bedrock geology mapping of the Animikie Basin and Midcontinent Rift southeast of Thunder Bay ▸ 1:50 000 scale bedrock geology mapping	ERGMS Core Program	New project – field work in 2022 ▸ *Summary of Field Work* (this volume, Article 11)
	Geology and mineral potential of Scarfe, Cobden, Thomson and Patton townships, Blind River area, Southern Province ▸ 1:20 000 scale bedrock geology mapping	ERGMS Core Program	Ongoing – bedrock geology mapping in Scarfe and part of Cobden townships in 2019; bedrock geology mapping in Patton and Thompson townships in 2022 ▸ *Summary of Field Work* article published in 2019 ▸ *Summary of Field Work* article (this volume, Article 14)
	Geology of the Brudenell area, Grenville Province ▸ multi-year 1:50 000 bedrock geology and compilation mapping project	ERGMS Core Program	Ongoing – field work completed ▸ Preliminary Map, MRD and OFR in progress
	Geology of the Cobden area, Grenville Province ▸ multi-year 1:50 000 scale bedrock geology and compilation mapping project	ERGMS Core Program	Ongoing – field work completed ▸ OFR and MRD published in 2017 ▸ Preliminary Map and OFR in progress
	Geology of the Perth area, Grenville Province ▸ multi-year 1:50 000 scale bedrock geology and compilation mapping project	ERGMS Core Program	Ongoing – field work completed ▸ OFR published in 2017; MRD published in 2019 ▸ Preliminary Map and OFR in progress
	Geology of Carleton Place area, Grenville Province ▸ multi-year 1:50 000 scale bedrock geology and compilation mapping	ERGMS Core Program	Ongoing –field work completed ▸ *Summary of Field Work* articles published in 2017, 2018, 2019 ▸ MRD, Preliminary Map and OFR in progress

Abbreviations: *MRD, Miscellaneous Release—Data; OFR, Open File Report.*

Table 4.1, *continued*.

Initiative	Project	ERGMS Core Program / Project Collaborator(s)	Project Progress
Proterozoic Initiative, *continued*	Geology of the Renfrew area, Grenville Province ▸ 1:50 000 scale bedrock geology and compilation mapping	ERGMS Core Program	Completed – field work completed ▸ *Summary of Field Work* article published in 2018 ▸ Preliminary Map and MRD submitted in 2022 for publication
Geology of Northeastern Ontario Initiative	Southern Swayze area (Abitibi greenstone belt) bedrock geology mapping project ▸ 1:20 000 scale bedrock geology mapping	ERGMS Core Program	Ongoing – bedrock geology mapping of Swayze, Dore township and part of Garnet Township in 2022 ▸ *Summary of Field Work* (this volume, Article 6), and published in 2015, 2016, 2017, 2018, 2019 ▸ Preliminary Map and MRD for Yeo and Chester townships area published in 2017 and 2018 ▸ Preliminary Map and MRD for Osway and Huffman townships and parts of Eric, Fingal and Arbutus townships published in 2018 ▸ Preliminary Map and MRD for Mallard, Marion, and part of Genoa townships published in 2019 and 2020
	Swayze area (Abitibi greenstone belt) metavolcanic evolution study ▸ regional and detailed bedrock geology mapping and detailed geochemistry and volcanology	ERGMS Core Program PhD thesis (T.P. Gemmell) Laurentian University–MERC (Metal Earth)	Ongoing – field work completed in 2021, analyses in progress ▸ *Summary of Field Work* articles published in 2017, 2021
	Structural and tectonic study of the Swayze area of the Abitibi greenstone belt	PhD thesis (Q. Wu) University of Waterloo	Ongoing – field work completed ▸ *Summary of Field Work* articles published in 2015, 2016
	Northern Swayze area (Abitibi greenstone belt) bedrock geology mapping project ▸ 1:20 000 scale bedrock geology mapping and 1:50 000 scale bedrock compilation	ERGMS Core Program	Ongoing – field work completed ▸ *Summary of Field Work* articles published in 2018, 2019 ▸ Preliminary Map and MRD for Penhorwood Township published in December 2020 ▸ Preliminary Map and MRD for Reeves and Sewell townships published in January 2021 ▸ OFR and compilation map in progress
		ERGMS Core Program (internship project – L.E.D. Vice)	Completed – mapping in Kenogaming Township completed ▸ *Summary of Field Work* article published in 2018 ▸ Preliminary Map published in December 2019 ▸ MRD published in December 2020
	Northeast Michipicoten greenstone belt bedrock geology mapping ▸ 1:20 000 scale bedrock geology mapping	ERGMS Core Program	Ongoing – bedrock geology mapping of Meath Township in 2022 ▸ Preliminary Map for Stover Township published in 2019 ▸ Preliminary Maps and MRDs for Copenace and Bruyere townships published in 2018 ▸ *Summary of Field Work* (this volume, Article 7) and articles published in 2016, 2017, 2018, 2019, 2021

Abbreviations: *MERC, Mineral Exploration Research Centre; MRD, Miscellaneous Release—Data; OFR, Open File Report.*

Table 4.1, ***continued****.*

Initiative	Project	ERGMS Core Program / Project Collaborator(s)	Project Progress
Geology of Northeastern Ontario Initiative, *continued*	Northeastern Michipicoten greenstone belt geochronological and structural study	ERGMS Core Program PhD thesis (L.E.D. Vice) Laurentian University–MERC (Metal Earth)	New project – field work in 2022 ▸ *Summary of Field Work* (this volume, Article 8)
	Geochronological investigation into the Hollinger Mine porphyries	ERGMS Core program	New project – completed ▸ *Summary of Field Work* (this volume, Article 5)
	Temagami greenstone belt bedrock mapping project ▸ 1:20 000 scale bedrock geology mapping	ERGMS Core Program	Ongoing – no mapping in 2021 or 2022, reconnaissance bedrock geology mapping in 2019 ▸ *Summary of Field Work* articles published in 2019, 2021
	Tectonometamorphic history of the Wawa–Abitibi terrane, northeastern Ontario: A deep crustal *P–T* transect from the Kapuskasing uplift to the Island Gold Mine	PhD thesis (J. Kendrick), University of Waterloo	Ongoing – sampling transects in 2018 and 2019, thesis analyses in progress ▸ *Summary of Field Work* articles published in 2018, 2019 ▸ Journal paper: Kendrick, Duguet and Yakymchuk (2022)
	The Rundle intrusive complex: Investigating oxidation processes related to gold mineralization in an Archean alkalic intrusive setting	MSc thesis (C.R. Small) Laurentian University–MERC (Metal Earth)	Ongoing – field work completed ▸ *Summary of Field Work* article published in 2018
	Bedrock geology and compilation of the Ramsey–Algoma intrusive complex and surrounding rocks ▸ multi-year bedrock geology mapping and compilation 1:100 000	ERGMS Core Program	Ongoing – no mapping in 2021 or 2022, reconnaissance bedrock geology mapping in 2019 ▸ *Summary of Field Work* articles published in 2019, 2020
Geology of Northwestern Ontario Initiative	Bedrock geology mapping of Marks and Conmee townships ▸ 1:20 000 scale bedrock geology mapping	ERGMS Core Program	Ongoing – Preliminary Map for Conmee Township and MRD in progress ▸ *Summary of Field Work* articles published in 2017, 2018
	Bedrock geology mapping of the Straw Lake–Esox Lake area, Rowan–Kakagi greenstone belt ▸ 1:20 000 scale bedrock geology mapping	ERGMS Core Program	New project – field work in 2022 ▸ *Summary of Field Work* (this volume, Article 10)
	Bedrock geology mapping of the Rowan–Kakagi lakes area ▸ 1:50 000 scale bedrock geology mapping	ERGMS Core Program	Ongoing – field work completed ▸ *Summary of Field Work* articles published in 2016, 2017 ▸ Preliminary Maps and MRD in progress
	Bedrock geology mapping and rare-mineral potential in the central Quetico Subprovince ▸ 1:50 000 scale bedrock geology mapping	ERGMS Core Program	Ongoing – no mapping in 2021 or 2022, bedrock mapping of the Georgia Lake area, Quetico Subprovince in 2019 ▸ *Summary of Field Work* articles published in 2019, 2020

Abbreviations: *MERC, Mineral Exploration Research Centre; MRD, Miscellaneous Release—Data.*

Table 4.1, *continued*.

Initiative	Project	ERGMS Core Program / Project Collaborator(s)	Project Progress
Geology of Northwestern Ontario Initiative, *continued*	Bedrock geology mapping of the Quetico Subprovince and related Proterozoic rocks northwest of Thunder Bay ▸ 1:50 000 scale bedrock geology mapping	ERGMS Core Program	Ongoing – mapping in 2022 ▸ *Summary of Field Work* this volume (Article 9) and articles published in 2019, 2020
	Geological compilation of the Red Lake greenstone belt, Uchi Subprovince	ERGMS Core Program	Ongoing – field work in 2022, compilation in progress ▸ Summary *of Field Work* article in 2021
	Petrology and geochemistry of mafic to ultramafic rocks of the Nakina area, English River Subprovince, northwestern Ontario	MSc thesis (S. Killins) Lakehead University	Ongoing – geochemical study of drill core donated to the Resident Geologist Program in Thunder Bay, sampling in fall 2020
2-D and 3-D Surficial Sediment Groundwater Mapping Initiative	Three-dimensional (3-D) mapping of Quaternary geology in central Simcoe County ▸ multi-year project to generate geologic model for groundwater assessment; Quaternary mapping and drilling	ERGMS Core Program PhD thesis (R.P.M. Mulligan) McMaster University	Ongoing – Quaternary drilling in 2015, 2016, 2017 and 2018 ▸ *Summary of Field Work* articles published in 2016, 2017, 2018, 2019 ▸ Preliminary Maps published in 2017 ▸ PhD thesis completed in 2019 ▸ 4 external papers published; 2 external papers in progress ▸ MRD, GRS and other Preliminary Maps in progress
	Three-dimensional (3-D) mapping of Quaternary deposits in the Niagara Peninsula ▸ multi-year project to generate geologic model for groundwater assessment; Quaternary mapping and drilling	ERGMS Core Program	Ongoing – field work completed ▸ *Summary of Field Work* articles published in 2013, 2014, 2015 (2), 2016, 2017 ▸ MRDs published in 2017 and 2020 ▸ Geophysical survey with GSC (data collected in 2015 and 2016, published in 2019) ▸ GRS in progress
	Regional groundwater systems mapping in the County of Simcoe, southern Ontario	ERGMS Core Program	Ongoing – groundwater sampling in 2018 and 2019 ▸ *Summary of Field Work* articles published in 2018, 2019
	Various groundwater geoscience projects (groundwater data mining, chemostratigraphic framework; 3-D model of surficial geology) in southern Ontario as part of the Federal groundwater program	Geological Survey of Canada (GSC)	Ongoing – OGS input into 3-D sediment model of southern Ontario ▸ GSC Summary Report published in 2020 by GSC (Russell and Kjarsgaard 2020) summarizes projects
	Surficial and subsurface sediment mapping in the City of Ottawa, eastern Ontario	ERGMS Core Program	Ongoing ▸ *Summary of Field Work* (this volume, Article 18) and article published in 2019

Abbreviations: *GRS, Groundwater Resources Study; MRD, Miscellaneous Release—Data.*

Table 4.1, *continued*.

Initiative	Project	ERGMS Core Program / Project Collaborator(s)	Project Progress
Aggregate Resources Initiative	Renfrew County Aggregate Resources Inventory	ERGMS Core Program	Ongoing ▸ results of mapping for sand and gravel and selected bedrock areas published in the ARO online database ▸ ARIP in progress
	Elgin County Aggregate Resources Inventory	ERGMS Core Program	Ongoing – field work completed ▸ ARIP in progress
	Regional Municipality of Niagara Aggregate Resources Inventory	ERGMS Core Program	Ongoing – field work completed ▸ ARIP in progress
	Haldimand County Aggregate Resources Inventory	ERGMS Core Program	Ongoing – field work completed in 2019 ▸ *Summary of Field Work* article published in 2019
	Identification and mapping of alkali–carbonate reactive layers in the Gull River Formation, near Kingston, Ontario (pilot project)	ERGMS Core Program	Ongoing – field work completed ▸ *Summary of Field Work* article published in 2018 ▸ OFR in progress
2-D and 3-D Paleozoic Bedrock Geology Groundwater Mapping Initiative	Bedrock aquifer, karst and Early Silurian sequence stratigraphic mapping project	ERGMS Core Program	Ongoing – field work completed in 2018 ▸ GRS 13 published 2020
	Update karst map for southern Ontario	ERGMS Core Program	Ongoing – mapping and sampling in 2019 ▸ *Summary of Field Work* article published in 2019
	Porosity and permeability analysis of deep subsurface Lockport Group ▸ project included compilation of 11 759 core analysis data sets from 150 wells and an update of more than 15 000 formational rank contacts	ERGMS Core Program and collaboration with GSC and OGSRL, NWMO and Mitacs (University of Western Ontario)	Ongoing – subsurface mapping completed 2021 ▸ GSC Open File in press; second in final review
	Clinton–Medina Group subsurface stratigraphy, formational rank QA/QC and subregional correlations	ERGMS Core Program and collaboration with OGSRL and Mitacs (University of Western Ontario), MSc thesis (R.H. Paterson) University of Western Ontario	Ongoing – subsurface mapping and core logging completed in fall 2021 ▸ *Summary of Field Work* (this volume, Article 19) and articles published in 2020, 2021 ▸ MSc thesis defended successfully by R.H. Paterson on October 24, 2022
	Upper Ordovician stratigraphy, sedimentology and isotope geochemistry of Upper Trenton Group Cobourg Formation (Collingwood Member) and basal Blue Mountain Formation (Rouge River Member) strata, southwestern Ontario	ERGMS Core Program and collaboration with OGSRL and Mitacs (University of Western Ontario), MSc thesis (D. Atasiei) University of Western Ontario	Ongoing – core logging and sampling will be completed by end of November 2022 ▸ *Summary of Field Work* (this volume, Article 20) and article published in 2021

Abbreviations: *ARIP, Aggregate Resources Inventory Paper; ARO, Aggregate Resources of Ontario; GRS, Groundwater Resources Study; GSC, Geological Survey of Canada; NWMO, Nuclear Waster Management Organization; OFR, Open File Report; OGSRL, Oil, Gas, and Salt Resources Library; QA/QC, quality assurance and quality control.*

Table 4.1, *continued*.

Initiative	Project	ERGMS Core Program / Project Collaborator(s)	Project Progress
2-D and 3-D Paleozoic Bedrock Geology Groundwater Mapping Initiative, *continued*	Stage 1 of Cambrian mapping initiative involves update of stratigraphy and sedimentology of basal mixed siliciclastic and carbonate strata across southern Ontario	ERGMS Core Program and collaboration with MNRF, OGSRL and University of Western Ontario researchers	New project – data gathering and start of core and cuttings logging and photography in 2022 ▸ *Summary of Field Work* (this volume, Article 21)
	Various groundwater geoscience projects (3-D geological model of Paleozoic bedrock) in southern Ontario as part of the Federal groundwater program	ERGMS Core Program and Geological Survey of Canada (GSC)	Ongoing ▸ 3-D model–version 2 and report published in 2021 by GSC (Carter et al. 2021) ▸ *Summary of Field Work* articles published in 2017, 2018
Paleozoic Initiative	Paleozoic geology of eastern Ontario ▸ 1:50 000 bedrock geology mapping; establish stratigraphic framework for the area	ERGMS Core Program	Ongoing – no mapping in 2021, bedrock mapping and stratigraphic work in 2019 ▸ *Summary of Field Work* (this volume, Article 23) and articles published in 2017, 2018, 2019
	South Niagara Peninsula bedrock geology mapping project	ERGMS Core Program	Ongoing – field work completed ▸ Preliminary Maps published in 2017 and 2018 ▸ 1 Preliminary Map in progress
	Paleozoic geology of eastern south-central Ontario ▸ 1:50 000 bedrock geology mapping	ERGMS Core Program	New project – field work in 2022 ▸ *Summary of Field Work* (this volume, Article 22)
	3-D Leapfrog® – updating Paleozoic digital map legend and lexicon for southern Ontario ▸ Phase 1 involves updates to Cambrian and Lower to Upper Ordovician succession of eastern and south-central Ontario	ERGMS Core Program	New project – no field work in 2022 ▸ Summary *of Field Work* article published in 2021
Ambient Groundwater Geochemistry Mapping Groundwater Initiative	Ambient Groundwater Geochemistry projects, southern Ontario ▸ data interpretation	ERGMS Core Program	Ongoing ▸ update of MRD 283 (MRD 283—Revision 2) published in December 2021
	Ambient Groundwater Geochemistry project, eastern Ontario (east Ottawa–Champlain Township)	ERGMS Core Program City of Ottawa	Ongoing – field work completed ▸ *Summary of Field Work* article published in 2017 ▸ update of MRD 283 (MRD 283—Revision 2) published in December 2021
	Ambient Groundwater Geochemistry project, eastern Ontario (west Ottawa groundwater study)	ERGMS Core Program City of Ottawa	Ongoing – field work completed ▸ *Summary of Field Work* article published in 2019 ▸ data incorporated into update of MRD 283 (MRD 283—Revision 2) published in December 2021
	Ambient Groundwater Geochemistry project, eastern Ontario (south Ottawa groundwater study)	ERGMS Core Program City of Ottawa	Ongoing – field work completed, analyses in progress ▸ *Summary of Field Work* (this volume, Article 25)

Abbreviations: *MNRF; Ministry of Natural Resources and Forestry; MRD, Miscellaneous Release—Data; OGSRL, Oil, Gas, and Salt Resources Library.*

Table 4.1, *continued*.

Initiative	Project	ERGMS Core Program / Project Collaborator(s)	Project Progress
Ambient Groundwater Geochemistry Mapping Groundwater Initiative, *continued*	Ambient Groundwater Geochemistry project, northeastern Ontario (North Bay)	ERGMS Core Program	Ongoing – North Bay area field work completed in 2018 ▸ data to be incorporated into new northern Ambient Groundwater database MRD ▸ *Summary of Field Work* article published in 2018
	Ambient Groundwater Geochemistry project, northeastern Ontario (Manitoulin and North Shore)	ERGMS Core Program	Ongoing – Manitoulin Island and North Shore areas completed in 2017 ▸ data to be incorporated into new northern Ambient Groundwater database MRD
	Ambient Groundwater Geochemistry project, northeastern Ontario (Sudbury)	ERGMS Core Program	Ongoing – Sudbury area completed in 2016 ▸ data to be incorporated into new northern Ambient Groundwater database MRD
	Characterizing the controls on groundwater chemistry in north-central Ontario	ERGMS Core Program MSc thesis (K.M. Dell) Queen's University	Ongoing – field work completed, analyses in progress ▸ *Summary of Field Work* article in 2020 ▸ OFR and northern Ontario Ambient Groundwater database MRD in progress
	Characterization of groundwater chemistry, bedrock topography, marine sediment thickness and their inter-relationships along the south bank of the Ottawa River between Ottawa and Hawkesbury, eastern Ontario	MSc thesis (S. Foubister) University of Ottawa	Ongoing – desktop study in progress
Provincial-Scale Compilation Initiative	Geochronology Inventory of Ontario (GeochrON) ▸ update current geochronology database and convert it to a Microsoft® Access® database and GIS format	ERGMS Core Program	Ongoing ▸ beta version of database released in 2019; update planned for 2022–2023
	Aggregate Resources of Ontario (ARO) compilation	ERGMS Core Program	Ongoing ▸ released in 2015, with updates published in 2019, 2020 and 2021
	Lake Geochemistry of Ontario (LakeGeochemON) compilation	ERGMS Core Program	Inaugural publication (beta version of database released) in March 2020
	Gold Fingerprinting: Major and trace elements associated with native gold working toward an open-source database	ERGMS Core Program Metal Earth, MERC–Laurentian University, ROM	Ongoing – laboratory and desktop study, data acquisition and analysis in progress ▸ *Summary of Field Work* (this volume, Article 15) and articles published in 2020, 2021

Abbreviations: *MERC, Mineral Exploration Research Centre (Laurentian University); MRD, Miscellaneous Release—Data; OFR, Open File Report; ROM, Royal Ontario Museum.*

The ERGMS main strategies consist of applying geoscience techniques

- to assess Earth resource potential to meet societal and government priorities;
- in areas of environmental priority to identify natural hazards related to geology;
- in areas of aggregate resource priority to meet societal and government priorities; and
- in areas of groundwater priority to meet societal and government priorities.

The ERGMS program is organized into 5 objectives based on the collection, interpretation, synthesis and distribution/communication of geoscience data and information as follows:

- provide the geological framework to support Earth resource exploration (minerals, metals, groundwater, aggregates, industrial minerals and energy), land-use planning, economic and infrastructure development and provide a geoscience baseline to help assess cumulative impacts of development;
- provide the geologic context to assess energy potential in the south and Far North;
- provide the geologic context to identify and interpret natural hazards to the environment and public health and safety;
- provide the geoscience framework to identify and inventory aggregate and industrial mineral resources for land-use planning, and resource and infrastructure development; and
- provide the geoscience framework to identify and inventory groundwater resources for use, protection and planning.

CORE GEOSCIENCE PROGRAM

The ERGMS strategies and objectives are addressed through its core geoscience program, which consists of a series of initiatives built upon one or more projects (*see* Table 4.1). In addition, the ERGMS participates in several collaborative projects to complement existing staff skills and capacity and to expand the amount of geoscience data available for the province. Collaborative projects are an important means to extend government resources and to capitalize on resources and expertise available in other organizations.

Initiatives

The ERGMS initiatives are based on geographic or functional groupings and are made up of

- team initiatives (i.e., Geology of Northeastern Ontario Initiative) consisting of individual projects that are designed to meet an overall goal; and
- individual, focussed projects.

The major initiatives of the ERGMS are subdivided into 6 broad categories outlined below and in Table 4.1.

➤ Initiatives involving geoscience mapping projects and the identification of Earth resources based on geographic area or geological region:

- Far North Land Use Planning;
- “Ring of Fire”;
- Geology of Northeastern Ontario;
- Geology of Northwestern Ontario;

- Proterozoic initiative;
- Paleozoic initiative;
- Surficial Geochemistry of Northern Ontario;
- Surficial Mapping of Northern Ontario;
- Surficial Geochemistry of Southern Ontario;
- Surficial Mapping of Southern Ontario.

➢ Initiatives involving identification of overburden and bedrock hydrostratigraphic units and contained groundwater resources at a regional scale; and understanding the geochemical effects of surface and groundwater interactions with rock and surficial media:

- two- and three-dimensional surficial sediment groundwater mapping;
- two- and three-dimensional Paleozoic bedrock geology groundwater mapping;
- ambient groundwater geochemistry.

➢ Initiatives involving aggregate and industrial mineral resource compilation and inventory studies:

- documentation and inventory of potential aggregate resources;
- documentation and inventory of potential industrial mineral resources.

➢ Initiatives involving geophysical projects:

- application of geophysical techniques in support of bedrock geology mapping;
- application of geophysical techniques in support of surficial sediment mapping;
- geophysics and rock properties data compilation.

➢ Initiatives involving provincial-scale mineral resource compilation and inventory studies:

- documentation of specific types of mineralization;
- developing inventories of various tectonic settings relevant to mineral exploration;
- ongoing maintenance of a database of geochronology work conducted in Ontario.

➢ Initiatives that involve collaborative project agreements with the GSC:

- participating in the bedrock and surficial geology working groups as part of the Canada–3D geological map compilation project for Canada.

To successfully develop and deliver on these initiatives, the ERGMS is engaged in numerous activities to develop, maintain and manage client, stakeholder and Indigenous relationships. The ERGMS is dedicated to maintaining relationships and exchanging technical information with partners, clients, stakeholders, regional prospector and land-owner associations and Indigenous communities. The ERGMS is also part of a number of external and internal committees to ensure these relationships are respectful, strong, long lasting and mutually beneficial.

OVERVIEW OF CURRENT COLLABORATIVE INITIATIVES AND PROJECTS

The ERGMS participates in several collaborative initiatives and projects (*see* Table 4.1). These collaborations are critical to maximizing individual organization resources and delivering the highest quality geoscience to all ERGMS clients and stakeholders.

Collaborations with Mineral Exploration Research Centre (MERC), Harquail School of Earth Sciences, Laurentian University

In the fall of 2016, Laurentian University was awarded $104 million for "Metal Earth" by the Canada First Research Excellence Fund (CFREF). The Fund's objective is to help Canadian postsecondary institutions excel globally in research areas that create long-term economic advantages for Canada. The premise of the Metal Earth project is to explain why some Archean greenstone terranes are rich in mineral deposits, whereas other, similar terranes are much less endowed despite broadly similar geology at surface. The multi-year Metal Earth project is beginning to wind down, but a limited field season was conducted in the summer 2022; details on these activities can be found on the Metal Earth Web site at https://merc.laurentian.ca/research/metal-earth [accessed November 30, 2022]. It is anticipated that there will be several technical sessions at the upcoming Geological Association of Canada–Mineralogical Association of Canada–Society for Geology Applied to Mineral Deposits (GAC–MAC–SGA) in Sudbury in May 2023 that will be devoted to reporting results of the Metal Earth program.

Collaborative Initiatives with the Geological Survey of Canada

In 2021, the federal government launched phase 6 of the Targeted Geoscience Initiative (TGI-6). The Targeted Geoscience Initiative (TGI) is a Government of Canada led, collaborative geoscience research program directed toward providing next generation knowledge and methods that will facilitate more effective targeting of buried mineral deposits. Several TGI-6 projects are being led by GSC geoscientists in Ontario and some ERGMS geoscientists have shared information and knowledge to support these various projects over the last year.

The ERGMS is also collaborating with the GSC as part of the Lands and Minerals Sector (LMS) of Natural Resources Canada (NRCan) Canada–3D digital geological map of Canada project. The Canada–3D project is a national collaboration involving the provincial and territorial geological surveys and the Geological Survey of Canada, operating under the auspices of the National Geological Surveys Committee (NGSC). The goal of this project is to develop the next generation of products to enhance the representation of Canada's subsurface geology.

Other Collaborative Projects

As mentioned previously, the ERGMS is involved with numerous governmental and academic partnerships to maximize geoscience resources and to augment the depth of geoscience projects in Ontario. The ERGMS also supported and/or participated in several collaborative projects with academic partners in 2022 (*see* Table 4.1).

Since 2013, the OGS has partnered with local municipalities in eastern Ontario to support the development of an Aquifer Capability Screening Tool (ACST). This support continued in 2022–2023 within southern rural parts of the City of Ottawa (this volume, Article 25).

The OGS has been involved in discussions with the geological surveys of Saskatchewan and Manitoba regarding a proposed lithodemic nomenclature proposal, especially as it applies to Precambrian rocks. It is anticipated that a draft document will be published in 2023. The OGS also provided the International Commission on Stratigraphic Classification (ISSC) of the International Union of Geological Sciences (IUGS) examples of the use of lithostratigraphic and lithodemic terminology in volcanic and metamorphic terrains for inclusion in a paper providing case studies in the use stratigraphic terminology (Pratt et al. 2022).

INTERJURISDICTIONAL AND COMMITTEE REPRESENTATION

Staff of the ERGMS represented the Ministry of Mines (Northern Development, Mines, Natural Resources and Forestry prior to June 2022), the OGS and other geoscience organizations on several interjurisdictional committees, internal committees and associations during the 2022–2023 fiscal year, which are summarized below:

- North American Commission on Stratigraphic Nomenclature (representing the Geological Association of Canada, and commissioner-at-large)
- International Commission on Stratigraphic Classification (ISSC)
- Paleontology Division of the Geological Association of Canada
- Great Lakes Geologic Mapping Coalition
- CAMIRO Geochemical Expert Committee
- Conservation Authorities Geosciences Committee
- Far North Information and Knowledge Management Working Group
- Growing the Green Belt to Protect Water Interministerial Team
- OPS Land Information Ontario (LIO) Imagery Group
- OPS Elevation Coordination & Consultation Committee (EC3)
- NDM Information Technology–Information Management (IT/IM) Strategy Committee
- Geoscience Laboratories (Geo Labs)–ERGMS Working Group
- Willet Green Miller Centre (WGMC) Joint Health and Safety Committee
- GIS in the Ontario Public Service (OPS) License Management Task Force
- Southern Ontario Stream Sediment Geochemistry Project Steering Committee
- Canadian Working Group on Regional Groundwater Flow Systems of the International Association of Hydrogeologists
- International Joint Commission (IJC) Great Lakes Science Advisory Board
- thesis committees and adjunct professorships at universities (Laurentian University, Carleton University, Ohio State University, University of Western Ontario, University of Toronto, Chinese Academy of Sciences)
- organizing committee for the 68th annual meeting of the Institute on Lake Superior Geology (ILSG) in Sudbury May 10–11, 2022 (Easton 2022a, 2022b, 2022c; Easton and Bennett 2022; Gordon, Généreux and Clarke 2022).
- Prospectors and Developers Association of Canada (PDAC) Health and Safety Committee (representing the Committee of Provincial and Territorial Geological Surveys)
- Prospectors and Developers Association of Canada (PDAC) Student–Industry Mineral Exploration Workshop (S-IMEW)

STAFFING CHANGES IN THE SECTION

Three staff have left the ERGMS over the past year: Bronwyn Azar, Stewart Hamilton and Elizabeth Priebe. Several new staff have accepted positions in ERGMS, and include Jeremy Creppin, Geological Assistant (acting); Nicholas Szumylo, Precambrian Geoscientist (acting); John Evangelatos, Geophysicist; Grant Hagedorn, Quaternary Geoscientist; Joseph Walker, Precambrian Geoscientist; and Gaëtan Launay, Precambrian Geoscientist. Manuel Duguet accepted the position of Senior Geoscience Leader for Northwestern Ontario. Brandon Portelance accepted an internship position.

LIST OF PUBLICATIONS[2]

Atasiei, D., Brunton, F.R., Jin, J. and Yeung, K.H. 2021. Stratigraphy and sedimentology of Upper Ordovician strata, with emphasis on Collingwood and Rouge River members, southern Ontario and Manitoulin Island: Project introduction; *in* Summary of Field Work and Other Activities, 2021, Ontario Geological Survey, Open File Report 6380, p.17-1 to 17-3.

Brunton, F.R., Béland Otis, C., Hahn, K.E. and Yeung, K.H. 2021. Progress on the development of a new stratigraphic framework for the Paleozoic geology of southern Ontario; *in* Summary of Field Work and Other Activities, 2021, Ontario Geological Survey, Open File Report 6380, p.16-1 to 16-9.

Burt, A.K., Ford, D., Holysh, S., Kalmo, K.J.J. and Russell, H.A.J., compilers. 2022. Regional-Scale groundwater geoscience in southern Ontario: The 2022 Ontario Geological Survey, Geological Survey of Canada, and Conservation Ontario Geoscientists Open House; Ontario Geological Survey, Open File Report 6379, 38p.

Burt, A.K., Mulligan, R.P.M., Brunton, F.R., Yeung, K.H., Spina, N.E. and Cheng, T. 2021. Improving geological nomenclature in Ontario well records; *in* Summary of Field Work and Other Activities, 2021, Ontario Geological Survey, Open File Report 6380, p.20-1 to 20-5.

Easton, R.M., Kamo, S.L. and Robichaud, L. 2021. Evidence for Geon 12 carbonatitic magmatism in the Wawa area: A distal manifestation of the Sudbury dike swarm mantle plume?; *in* Summary of Field Work and Other Activities, 2021, Ontario Geological Survey, Open File Report 6380, p.10-1 to 10-11.

Easton, R.M., Rainsford, D.R.B. and Préfontaine, S. 2021. Preliminary Interpretation of the Saganash Lake area aeromagnetic survey, northeastern Ontario; *in* Summary of Field Work and Other Activities, 2021, Ontario Geological Survey, Open File Report 6380, p.6-1 to 6-11.

Ferguson, S.A. 2021. Geological compilation map of the North Caribou–Wachusk lakes area, North Caribou greenstone belt, northwestern Ontario; *in* Summary of Field Work and Other Activities, 2021, Ontario Geological Survey, Open File Report 6380, p.5-1 to 5-8.

Gao, C. and Turton, C.L. 2021. Updates on drill-core logging in southern James Bay Lowland, Far North of Ontario; *in* Summary of Field Work and Other Activities, 2021, Ontario Geological Survey, Open File Report 6380, p.15-1 to 15-9.

Gemmell, T.G. 2021. Geological investigation of the Shunsby base metal prospects area, southern Swayze area of the Abitibi greenstone belt; *in* Summary of Field Work and Other Activities, 2021, Ontario Geological Survey, Open File Report 6380, p.7-1 to 7-9.

Gordon, C.A. and Péloquin, A.S. 2021. Proterozoic mafic intrusions of the Sudbury area: Compilation and characterization project; *in* Summary of Field Work and Other Activities, 2021, Ontario Geological Survey, Open File Report 6380, p.11-1 to 11-6.

[2] *This list provides references for publications produced by ERGMS, during the period from December 1, 2021 to November 30, 2022, inclusive, comprising 4 Open File Reports, 3 Miscellaneous Releases—Data (MRD) and 1 Groundwater Resources Study.*

Hahn, K.E. 2021. Pyrrhotite distribution in Ontario: Near-surface occurrences and discussion of deleterious effects in concrete; Ontario Geological Survey, Miscellaneous Releases—Data 395.

Hamilton, S.M. 2021. Ambient groundwater geochemical and isotopic data for southern Ontario, 2007–2019; Ontario Geological Survey, Miscellaneous Releases—Data – Revision 2.

Hamilton, S.M., Dell, K.M. and Priebe, E.H. 2021. Ambient groundwater geochemical database compilations for Ontario, 2021–2022: Summary of available data and forthcoming publications; *in* Summary of Field Work and Other Activities, 2021, Ontario Geological Survey, Open File Report 6380, p.19-1 to 19-9.

Handley, L.A. and Dyer, R.D. 2022. Geochemistry and soil gas hydrocarbon data from a peat sampling transect over Eagle's Nest nickel-copper and Blackbird chromium deposits, McFaulds Lake ("Ring of Fire") area, northern Ontario; Ontario Geological Survey, Miscellaneous Releases—Data 399.

Hechler, J.H., Easton, R.M., Préfontaine, S., Hamilton, S.M., Rainsford, D.R.B., Robichaud, L. and Cormier, R. 2021. Earth Resources and Geoscience Mapping Section: 2021–2022 program and projects overview; *in* Summary of Field Work and Other Activities, 2021, Ontario Geological Survey, Open File Report 6380, p.4-1 to 4-24.

MacDonald, P.J. and Kamo, S.L. 2021. New uranium–lead geochronology from the Temagami greenstone belt, northeastern Ontario; *in* Summary of Field Work and Other Activities, 2021, Ontario Geological Survey, Open File Report 6380, p.8-1 to 8-9.

MacDonald, P.J. and Malegus, P.M. 2021. Introduction to the Red Lake bedrock geology mapping compilation project, northwestern Ontario; *in* Summary of Field Work and Other Activities, 2021, Ontario Geological Survey, Open File Report 6380, p.9-1 to 9-5.

Magnus, S.J. 2022. Volcanic stratigraphy of the western Schreiber–Hemlo greenstone belt and Mesoproterozoic geology of the north shore of Lake Superior, Terrace Bay area, northwestern Ontario; Ontario Geological Survey, Open File Report 6377, 40p.

Melo-Gómez, J.D., Hastie, E.C.G., Gibson, H.L., Tait, K.T. and Petrus, J.A. 2021. Gold fineness across Ontario: An update on the Gold Fingerprinting Project; *in* Summary of Field Work and Other Activities, 2021, Ontario Geological Survey, Open File Report 6380, p.13-1 to 13-9.

Metsaranta, R.T. and Kamo, S.L. 2021. A uranium–lead baddeleyite age for the Midcontinent Rift–related Lone Island Lake intrusion, northwestern Ontario; *in* Summary of Field Work and Other Activities, 2021, Ontario Geological Survey, Open File Report 6380, p.12-1 to 12-8.

Ontario Geological Survey 2021. Summary of Field Work and Other Activities, 2021; Ontario Geological Survey, Open File Report 6380, 184p.

Paterson, R.H., Brunton, F.R., Jin, J., Phillips, A.R. and Yeung, K.H. 2021. Subsurface correlation of the Silurian Clinton and Medina groups, southwestern Ontario; *in* Summary of Field Work and Other Activities, 2021, Ontario Geological Survey, Open File Report 6380, p.18-1 to 18-9.

Priebe, E.H., Ford, D., Holysh, S., Nadeau, J.E. and Russell, H.A.J., compilers. 2022. Regional-scale groundwater geoscience in southern Ontario: The 2021 Ontario Geological Survey, Geological Survey of Canada, and Conservation Ontario Geoscientists Open House; Ontario Geological Survey, Open File Report 6378, 24p.

Priebe, E.H. and Hamilton, S.M. 2022. Tritium in shallow groundwater of southern Ontario; Ontario Geological Survey, Groundwater Resources Study 20.

Rainsford, D.R.B. and Biswas, S. 2021. Summary of geophysical projects and activities; *in* Summary of Field Work and Other Activities, 2021, Ontario Geological Survey, Open File Report 6380, p.14-1 to 14-9.

REFERENCES

Carter, T.R., Logan, C.E., Clark, J.K., Russell, H.A.J., Brunton, F.R., Cachunjua, A., D'Arienzo, M., Freckelton, C., Rzyszczak, H., Sun, S. and Yeung, K.H. 2021. A three-dimensional geological model of the Paleozoic bedrock of southern Ontario (version 2); Geological Survey of Canada, Open File 8795, 103p. doi.org/10.4095/328297

Easton, R.M., editor. 2022a. 68th Institute on Lake Superior Geology, Sudbury, Ontario, Proceedings, Part 1 — Program and Abstracts, v.68, part 1, 57p., available from Archives & Digital Collections at Lakehead University Library, digitalcollections.lakeheadu.ca/items/show/6317.

——— editor. 2022b. 68th Institute on Lake Superior Geology, Sudbury, Ontario, Proceedings, Part 2 — Field Trip Guidebooks, v.68, part 2, 255p., available from Archives & Digital Collections at Lakehead University Library, digitalcollections.lakeheadu.ca/items/show/6317.

——— 2022c. Field Trip 2 – Geology of the Grenville Front and the Grenville Front tectonic zone in the Sudbury area; *in* 68th Institute on Lake Superior Geology, Sudbury, Ontario, Proceedings, v.68, part 2, p.102-146, available from Archives & Digital Collections at Lakehead University Library, digitalcollections.lakeheadu.ca/items/show/6317.

Easton, R.M. and Bennett, G. 2022. Field Trip 5 – An overview of the Huronian Supergroup in the Elliot Lake area; in 68th Institute on Lake Superior Geology, Sudbury, Ontario, Proceedings, v.68, part 2, p.199-255, available from Archives & Digital Collections at Lakehead University Library, digitalcollections.lakeheadu.ca/items/show/6317.

Généreux, C-A., Tinkham, D.K. and Lafrance, B. 2021. On the role of shock melting and anatexis in breccia formation: Southern Sudbury impact structure, Canada; Precambrian Research, v.363, paper 106346, 25p. doi.org/10.1016/j.precamres.2021.106346

Gordon, C., Généreux, C-A. and Clarke, B. 2022. Field Trip 3 – Magmatism and brecciation in the Footwall rocks in the southwestern Sudbury Structure; *in* 68th Institute on Lake Superior Geology, Sudbury, Ontario, Proceedings, v.68, part 2, p.147-180, available from Archives & Digital Collections at Lakehead University Library, digitalcollections.lakeheadu.ca/items/show/6317.

Kendrick, J., Duguet, M. and Yakymchuk, C. 2022. Diversification of Archean tonalite-trondhjemite-granodiorite suites in a mushy middle crust; Geology, v.50, p.76-80. doi.org/10.1130/G49287.1

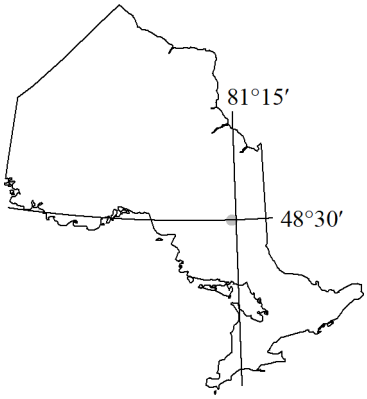
Ontario Geological Survey 2011. 1:250 000 scale bedrock geology of Ontario; Ontario Geological Survey, Miscellaneous Release—Data 126 – Revision 1.

Pratt, B.R., Finney, S.C., Easton, R.M. and Piller, W.E. 2022. Lithostratigraphy: Formation of the Formation; Newsletters of Stratigraphy, 24p., published online October 7, 2022. doi.org/10.1127/nos/2022/0732

Russell, H.A.J. and Kjarsgaard, B.A., editors. 2020. Southern Ontario groundwater project 2014–2019: Summary report; Geological Survey of Canada, Open File 8536, 245p. doi.org/10.4095/321078

von Gunten, K., Hamilton, S.M., Zhong, C., Nesbø, C., Jiaying, L., Muehlenbachs, K., Konhauser, K.O. and Alessi, D.S. 2018. Electron donor-driven bacterial and archaeal community patterns along forest ring edges in Ontario, Canada; Environmental Microbiology Reports, v.10, p.663-672.

5. New Geochronological Data from the Hollinger Mine, Timmins Area, Abitibi Greenstone Belt, Northeastern Ontario



P.J. MacDonald[1] and S.L. Kamo[2]

[1]Earth Resources and Geoscience Mapping Section, Ontario Geological Survey, Sudbury, Ontario P3E 6B5
[2]Jack Satterly Geochronology Laboratory, Department of Earth Sciences, University of Toronto, Toronto, Ontario M5S 3B1

INTRODUCTION

The Timmins gold camp is the worlds largest Archean orogenic greenstone hosted gold camp with over 70 million ounces gold (Moz) produced (Dubé et al. 2020). The largest deposit in the camp is the giant approximately 30 Moz Hollinger–McIntyre gold deposit (Dubé et al. 2017; Azadbakht et al. 2022). Mineralization at the Hollinger–McIntyre deposit is predominantly hosted in mafic metavolcanic flows of the 2710–2704 Ma Tisdale volcanic episode and, to a lesser extent, in quartz-feldspar porphyry intrusions with reported emplacement between 2691 and 2688 Ma (Corfu et al. 1989; Ayer et al. 2002; Thurston et al. 2008; Monecke et al. 2017; Dubé et al. 2017; Figure 5.1). The timing of gold mineralization postdates the intrusions, with an age, using the rhenium-osmium (Re/Os) method, for the molybdenite within the deposit determined at 2672±7 Ma (Bateman et al. 2004) and supported by an albitite dike age at 2672.8±1.1 Ma (Corfu et al. 1989; Ayer et al. 2005) that is cut by a gold-bearing quartz vein.

Throughout the Abitibi greenstone belt, syntectonic intrusions, such as the felsic to intermediate porphyries in Timmins, show a spatial association with gold mineralization (Burrows 1925; Robert 2001; Dubé et al. 2020; Hastie et al. 2022). The timing of intrusions is important to constrain the mineralization genetically related to the intrusions as well as to constrain deformation, crustal architecture and crustal evolution prior to mineralization (Ispolatov et al. 2008; MacDonald and Piercey 2019; Dubé et al. 2020). Determining the age of these intrusive rocks is often challenging because of zircon inheritance and overgrowths (Ispolatov et al. 2008; MacDonald, Hastie and Davis 2017).

Previous age determinations on porphyry intrusions in the Hollinger–McIntyre gold deposit were determined on air-abraded zircon grains using isotope dilution thermal ionization mass spectrometry (ID-TIMS) methods (Corfu et al. 1989). To test the validity of previous age determinations, a sample was collected from a quartz-feldspar porphyry intrusion located within Hollinger open pit. Uranium–lead (U/Pb) zircon geochronology was performed on the sample, first via laser ablation inductively coupled plasma mass spectrometry (LA-ICP–MS) methods. Then 4 of the chemically abraded apparent youngest zircons were reanalyzed by CA-ID-TIMS geochronology methods. The analytical data collected, age determinations and a brief discussion of the results are presented in this article.

Summary of Field Work and Other Activities, 2022,
Ontario Geological Survey, Open File Report 6390, p.5-1 to 5-11.

© King's Printer for Ontario, 2022

URANIUM–LEAD GEOCHRONOLOGY ANALYTICAL METHODS

Sample preparation and isotopic analyses were carried out at the Jack Satterly Geochronology Laboratory (JSGL) at the University of Toronto. The sample was crushed and milled using standard methods (jaw crusher and Bico disk mill, respectively). Heavy mineral separation was carried out on a Wilfley table, followed by paramagnetic separation with a Frantz isodynamic separator and density separation using methylene iodide. Final sample separation was by hand picking under a microscope. Uranium–lead analysis was carried out by LA-ICP–MS methods, then select grains were reanalyzed by CA-ID-TIMS methods.

Prior to LA-ICP–MS analysis, grains were mounted in epoxy, polished and imaged with backscattered electrons (BSE) using a JEOL JSM6610-Lv scanning electron microscope to detect phases of growth that may have different ages. Imaged grains were partially ablated using a 193 nm New Wave excimer laser and an Agilent 7900 ICP–MS. The laser was generally operated at 5 Hz and 5 J/cm^2 fluence with beam diameter of 20 µm. Data were collected on ^{88}Sr (10 ms), ^{206}Pb (30 ms), ^{207}Pb (90 ms), ^{232}Th (10 ms) and ^{238}U (20 ms). Spots were pre-ablated for 1 second (5 pulses) with a large beam diameter to clean the surface, followed by a 10 second period of baseline accumulation. The laser beam was then turned on for 25 seconds of data collection, followed by a washout period. About 150 measurement cycles

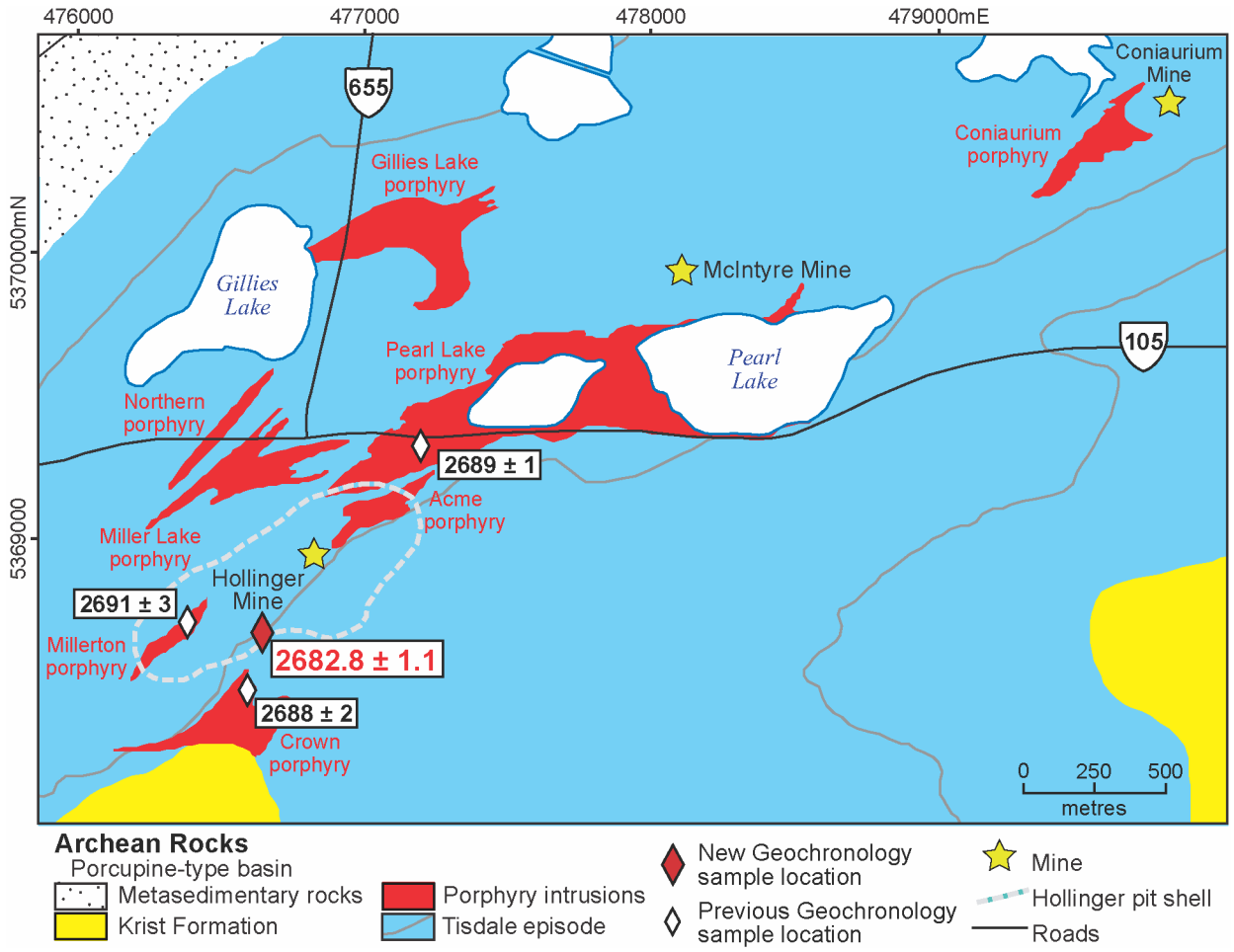


Figure 5.1. Simplified surface geology map of the Hollinger–McIntyre gold deposit showing mines, porphyry intrusions and geochronology sample locations (*modified from* Ferguson 1966; MacDonald, Piercey and Hamilton 2005). Universal Transverse Mercator (UTM) co-ordinates provided in North American Datum 1983 (NAD83), Zone 17.

per sample were produced and ablation pits were 15 μm deep. Data were edited and reduced using in-house VBA software (UtilLAZ program). The $^{206}Pb/^{238}U$ ratios showed increasing fractionation throughout zircon runs, whereas the $^{207}Pb/^{206}Pb$ profiles were usually flat. No corrections were made for common Pb because the ^{204}Pb peak is too small to be measured precisely and common Pb is usually insignificant for unaltered Precambrian zircon. Isotope ^{88}Sr was monitored to detect intersection of the beam with alteration or inclusions. Data showing high strontium or irregular time resolved profiles were either averaged over restricted strontium-free time windows or rejected. A rough estimate of the Th/U value of zircon was also measured, as the ratio is not constant in the standard. Two zircon standards were used: DD85-17, a quartz diorite from the Marmion batholith in northwest Ontario (3002±2 Ma: Tomlinson et al. 2003) and DD91-1, a monzodiorite from the Pontiac province of Quebec (2682±1 Ma: Davis 2002). Sets of 4 sample measurements were bracketed by standard measurements, differences between standards were time interpolated to correct sample measurements.

Prior to CA-ID-TIMS analysis, 10 of the apparent youngest zircon grains from LA-ICP–MS analysis were removed from the original epoxy mount and chemically abraded by partial dissolution in HF and HNO_3 in Teflon® dissolution vessels at 200°C for 2 hours (chemical etch). Zircon was rinsed in 7N HNO_3 at room temperature prior to dissolution. A $^{205}Pb–^{235}U$ spike was added to Krogh-type Teflon® dissolution capsules during sample loading. The zircon grains were dissolved using approximately 0.10 mL of concentrated HF acid and 0.02 mL of 7N HNO_3 at 200°C for 2 to 3 days. Samples were dried to a precipitate and redissolved in 0.15 mL of 3N HCl overnight (Krogh 1973). Uranium and lead were isolated from zircon using HCl in miniaturized 50 μL anion exchange columns, dried in phosphoric acid, deposited onto outgassed rhenium filaments with silica gel (Gerstenberger and Haase 1997), and analyzed with a VG354 mass spectrometer using a Daly detector in pulse counting mode. Corrections to $^{206}Pb–^{238}U$ and $^{207}Pb/^{206}Pb$ ages for initial ^{230}Th disequilibrium in zircon were made assuming a Th/U ratio in the magma of 4.2. Common lead was assigned to procedural lead blank for zircon. Dead time of the measuring system for lead and uranium was 16 and 14 ns, respectively. The mass discrimination correction for the Daly detector is constant at 0.05% per atomic mass unit. Amplifier gains and Daly characteristics were monitored using the SRM 982 Pb standard. Thermal mass discrimination corrections are 0.10% per atomic mass unit for lead and uranium. VG Sector software was used for CA-ID-TIMS data acquisition and in-house Visual Basic software (UtilAge) was used for data reduction.

Decay constants are those of Jaffey et al. (1971). Plotting and age calculations were done using Isoplot 3.00 (Ludwig 2003). All age errors quoted, and error ellipses in the diagrams are given at 95% confidence interval.

RESULTS

Sample 20PMT001 was collect by Newmont Porcupine staff from the Hollinger gold mine pit (UTM 476638E 5368665N, NAD83 Zone 17; *see* Figure 5.1). The sample was initially reported as being from the Acme porphyry, but its location most likely indicates it is from a northern apophysis of the Crown porphyry (*see* Figure 5.1). The quartz-feldspar porphyry intrusion sample is similar to other porphyry samples previously collect by the lead author (*see* MacDonald, Piercey and Hamilton 2005), with the porphyry intrusion having undergone intense hydrothermal alteration and deformation and is now best described as a quartz-sericite schist (Photo 5.1A).

The sample yielded a small amount of zircon as mixed populations of small thin, euhedral, tabular, light brown, cracked grains to large, clear fragments with some reddish alteration and inclusions (Photo 5.1B). Backscattered electron images show zoned, patchy and cracked grains with inclusions (Photos 5.1C and 5.1D). Of 55 zircons analyzed by LA-ICP–MS, 7 were discarded because of alteration or irregular profiles (Table 5.1). Of the remaining 48 analyses, 11 were between 2703 and 2737 Ma and

are interpreted as inherited grains (*see* Table 5.1). The 37 youngest U/Pb analyses range in age from 2639 to 2694 Ma (*see* Table 5.1), scatter within error and give an age estimate of 2678±5 Ma (N=37; MSWD = 0.9; Figures 5.2A, 5.2B and 5.2C).

To test the accuracy of the 2678±5 Ma porphyry intrusion age, CA-ID-TIMS was implemented. Ten of the apparent youngest zircon grains were removed from the original epoxy mount and chemically abraded. Only a brief 2-hour etch was given to preserve the relatively few number of "younger" grains available. Four of the 10 zircon crystals were selected for analysis, based on their good state of preservation and lack of alteration. Three (Z1–Z3) gave overlapping, sub-concordant results (0.8–1.4% discordant) with a mean age of 2682.8±1.1 Ma (Figure 5.2D; Table 5.2). If Z1 to Z3 are assumed to have undergone earlier minor lead loss (for example at 200 Ma), an upper intercept of 2683.7 Ma is given, which is within error of the mean age. A fourth (Z4) datum is slightly more discordant (2.5%) and older at 2689.0±2.5 Ma and is not considered in the age calculation (*see* Figure 5.2D; *see* Table 5.2).

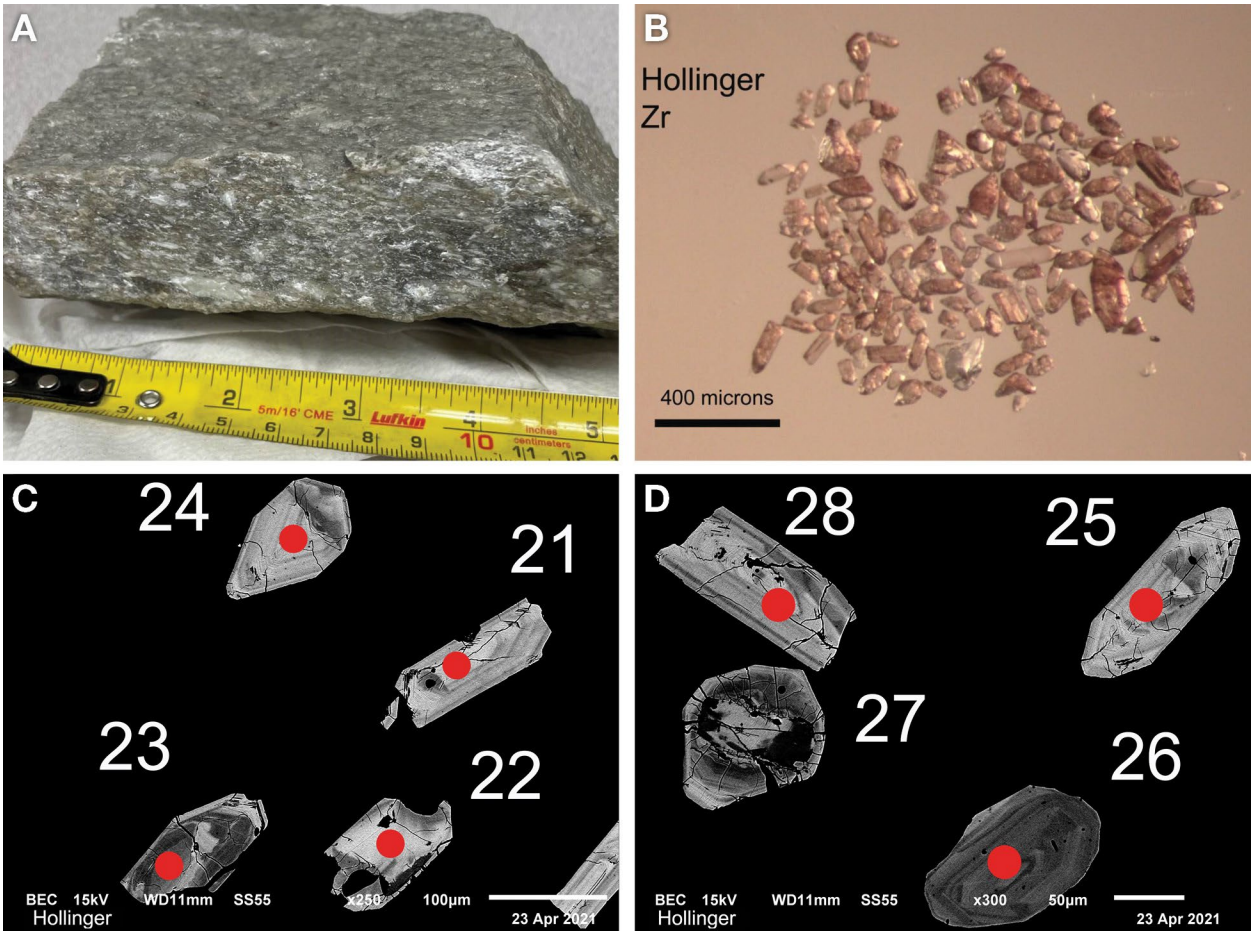


Photo 5.1. Selected photographs of quartz-feldspar porphyry intrusion, sample number 20PMT001, Hollinger mine pit. **A)** Rock sample image of quartz-sericite schist (quartz-feldspar porphyry). **B)** Zircon grain population image. **C)** Backscattered electron images of selected grains (21–24) showing zoning, patchiness, fracturing and inclusions. Red spots represent the approximate locations of laser ablation pits (20 µm diameter). Grain 24 was analyzed by LA-ICP–MS and CA-ID-TIMS methods. **D)** Backscattered electron images of selected grains (25–28) showing zoning, patchiness, fracturing and inclusions. Red spots represent the approximate locations of laser ablation pits (20 µm diameter). Grains 25 and 28 were analyzed by LA-ICP–MS and CA-ID-TIMS methods.

A re-interpretation of the age of emplacement of the porphyry intrusion at 2682.8±1.1 Ma is presented. This is within uncertainty of the LA-ICP–MS determined age, but may represent a more accurate estimate of the time of emplacement of the porphyry.

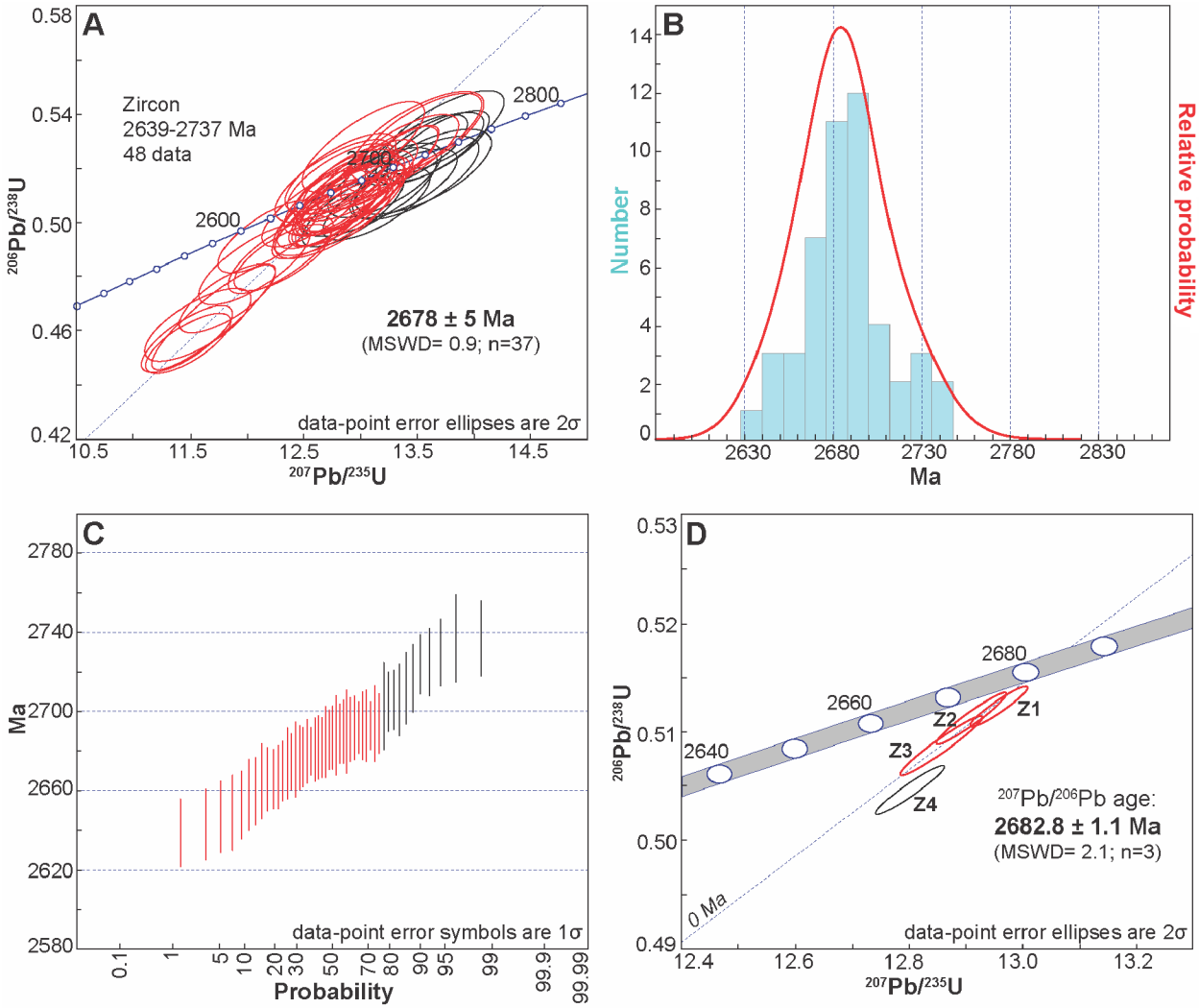


Figure 5.2. Concordia diagrams and probability plots of quartz-feldspar porphyry intrusion, sample number 20PMT001, Hollinger mine pit. **A)** Concordia plot showing U/Pb LA-ICP–MS isotopic data obtained from zircon in a polished epoxy grain mount. The red ellipses represent data for the younger population and the black ellipses represent data for inherited grains, (*modified from* Sutcliffe 2021). **B)** Relative probability density plot of $^{207}Pb/^{206}Pb$ ages on polished zircon (*modified from* Sutcliffe 2021). **C)** Linearized probability plot of $^{207}Pb/^{206}Pb$ ages on polished zircon (*modified from* Sutcliffe 2021). Error bars colours as in B. **D)** Concordia diagram of sample analyzed by U/Pb CA-ID-TIMS (*modified from* Kamo 2022). The red ellipses represent data for the younger population and the black ellipse represents data for an inherited grain.

Table 5.1. Zircon U/Pb LA-ICP–MS isotopic data from sample 20PMT001, quartz-feldspar porphyry intrusion, Hollinger Pit, Timmins.

Analysis No.	U (ppm)	^{206}Pb (ppm)	Th/U	^{207}Pb/^{235}U	1σ	^{206}Pb/^{238}U	1σ	Error Corr.	^{207}Pb/^{206}Pb Age	1σ	^{207}Pb/^{235}U Age	1σ	^{206}Pb/^{238}U Age	1σ	% Disc.
20PMT001: Quartz-feldspar porphyry intrusion, Hollinger pit, Tisdale Township (UTM 476638E 5368665N, NAD83, Zone 17)															
13k *	1028	479	0.44	11.120	0.179	0.4658	0.0057	0.76126	2588	17	2533	15	2465	25	6
7z *	592	295	0.32	12.057	0.167	0.4991	0.0056	0.81309	2608	13	2609	13	2610	24	0
24z	2025	1002	0.45	12.182	0.181	0.4948	0.0055	0.74102	2639	17	2618	14	2592	24	2
21	1332	703	0.38	13.021	0.221	0.5279	0.0068	0.76422	2643	18	2681	16	2732	29	−4
48f *	221	121	0.39	13.596	0.403	0.5504	0.0141	0.86616	2645	25	2722	28	2827	59	−8
14	442	229	0.28	12.820	0.201	0.5183	0.0059	0.72522	2647	18	2667	15	2692	25	−2
25p	1610	830	0.48	12.758	0.212	0.5153	0.0062	0.72764	2649	19	2662	16	2679	27	−1
28p	763	393	0.32	12.805	0.186	0.5159	0.0054	0.72661	2653	17	2665	14	2682	23	−1
22	1256	609	1.90	12.060	0.202	0.4845	0.0061	0.75793	2658	18	2609	16	2547	27	5
54f	684	346	0.44	12.594	0.191	0.5052	0.0058	0.75305	2660	17	2650	14	2636	25	1
53k	422	195	0.43	11.559	0.192	0.4622	0.0055	0.71875	2665	19	2569	16	2449	24	10
15	829	428	0.26	12.906	0.174	0.5158	0.0052	0.74420	2666	15	2673	13	2681	22	−1
17p	771	396	0.88	12.852	0.182	0.5138	0.0054	0.74628	2666	16	2669	13	2673	23	0
52c	527	249	0.46	11.817	0.173	0.4720	0.0052	0.74859	2667	16	2590	14	2492	23	8
42.2r	927	424	0.53	11.461	0.164	0.4570	0.0050	0.76587	2670	15	2561	13	2426	22	11
20z	1261	643	0.48	12.822	0.205	0.5101	0.0060	0.73601	2674	18	2667	15	2657	26	1
10pc	514	239	0.37	11.697	0.223	0.4651	0.0079	0.89145	2675	14	2580	18	2462	35	10
11c	808	415	0.30	12.908	0.195	0.5130	0.0051	0.65748	2676	19	2673	14	2670	22	0
34k	786	358	0.52	11.472	0.154	0.4554	0.0045	0.73976	2677	15	2562	13	2419	20	12
49kc	853	416	0.30	12.291	0.190	0.4880	0.0058	0.76857	2677	16	2627	15	2562	25	5
3U	583	300	0.11	12.982	0.147	0.5146	0.0045	0.78172	2680	12	2678	11	2676	19	0
47k	716	370	0.40	13.050	0.184	0.5172	0.0054	0.74112	2680	16	2683	13	2687	23	0
43p	762	383	0.33	12.705	0.183	0.5033	0.0053	0.73106	2681	16	2658	14	2628	23	2
19kc	838	427	0.40	12.848	0.185	0.5087	0.0057	0.77108	2682	15	2669	14	2651	24	1
55	417	203	0.47	12.304	0.174	0.4870	0.0050	0.72262	2682	16	2628	13	2558	22	6
46p	635	325	0.43	12.948	0.209	0.5116	0.0061	0.73488	2685	18	2676	15	2663	26	1
32.2r	503	251	0.56	12.620	0.167	0.4985	0.0049	0.73674	2686	15	2652	12	2607	21	4

Notes: *Analyses are sorted from highest to lowest $^{207}Pb/^{206}Pb$ age.*
Grain characteristics: k = cracked; z = oscillatory zoning; f = fragment; p = patchy zonation; c = core; r - thin rim; u = homogeneous; U = high uranium (bright).
** Omitted because of high Sr and/or irregular profile.*
Error Corr. is correlation coefficients of X–Y errors on the concordia plot.
Disc. is percent discordance for the given $^{207}Pb/^{206}Pb$ age.
Relation between ages and concordia co-ordinates: $Y = {}^{206}Pb/^{238}U = EXP(L238\times(206\text{-}238Age)) - 1$; $X = {}^{207}Pb/^{235}U = EXP(L235\times(207\text{-}235Age)) - 1$.
$^{207}Pb/^{206}Pb = 137.88 \times X/Y$; U decay constants (L238 & L235) from *Jaffey et al. (1971), where L238 = 1.55125 $\times 10^{10}$/yr; L235 = 9.8485 $\times 10^{10}$/yr.*

Table 5.1, *continued*.

Analysis No.	U (ppm)	^{206}Pb (ppm)	Th/U	^{207}Pb/^{235}U	1σ	^{206}Pb/^{238}U	1σ	Error Corr.	^{207}Pb/^{206}Pb Age	1σ	^{207}Pb/^{235}U Age	1σ	^{206}Pb/^{238}U Age	1σ	% Disc.
32.1c	383	194	0.35	12.870	0.184	0.5080	0.0053	0.73393	2687	16	2670	13	2648	23	2
37z	402	203	0.37	12.808	0.240	0.5052	0.0071	0.75285	2688	20	2666	18	2636	30	2
18kc	619	322	0.31	13.195	0.198	0.5202	0.0062	0.79174	2689	15	2694	14	2700	26	−1
26z	171	91	0.97	13.497	0.241	0.5317	0.0068	0.71836	2690	21	2715	17	2749	29	−3
39z	1132	577	0.35	12.930	0.185	0.5093	0.0053	0.73071	2690	16	2675	13	2654	23	2
56	1127	574	0.40	12.944	0.198	0.5097	0.0059	0.76131	2691	16	2676	14	2655	25	2
9z	533	278	0.39	13.254	0.178	0.5217	0.0057	0.81287	2692	13	2698	13	2707	24	−1
51.2r	474	239	0.26	12.804	0.180	0.5037	0.0052	0.73848	2692	16	2665	13	2630	22	3
1cU	600	302	0.25	12.795	0.153	0.5031	0.0048	0.80299	2693	12	2665	11	2627	21	3
12p	104	56	0.70	13.543	0.215	0.5326	0.0061	0.72062	2693	18	2718	15	2752	26	−3
42.1c	244	128	0.64	13.363	0.204	0.5255	0.0058	0.72629	2693	17	2706	14	2723	25	−1
33cU	542	273	0.27	12.813	0.173	0.5037	0.0051	0.74460	2694	15	2666	13	2630	22	3
38zr	1046	525	0.42	12.762	0.213	0.5017	0.0061	0.73586	2694	19	2662	16	2621	26	3
45p	147	75	1.23	13.076	0.244	0.5112	0.0067	0.70515	2703	22	2685	18	2662	29	2
16p	339	179	0.91	13.488	0.185	0.5267	0.0053	0.73070	2705	15	2714	13	2728	22	−1
4p	49	25	0.32	13.211	0.205	0.5155	0.0056	0.70144	2706	18	2695	15	2680	24	1
35k	609	307	0.63	12.930	0.183	0.5045	0.0055	0.76363	2706	15	2675	13	2633	23	3
36kp	326	174	0.56	13.718	0.223	0.5332	0.0063	0.73341	2712	18	2730	15	2755	27	−2
5p	81	43	0.86	13.607	0.196	0.5273	0.0054	0.71203	2717	17	2723	14	2730	23	−1
8p	108	57	0.50	13.683	0.185	0.5281	0.0053	0.74681	2724	15	2728	13	2734	22	0
41c *	191	86	0.70	11.677	0.198	0.4507	0.0056	0.73625	2724	19	2579	16	2398	25	14
6f	69	35	0.68	13.137	0.194	0.5068	0.0054	0.72247	2725	17	2690	14	2643	23	4
51.1c	284	146	0.78	13.375	0.193	0.5143	0.0052	0.69682	2730	17	2707	14	2675	22	2
23p	191	99	0.75	13.491	0.226	0.5164	0.0062	0.71838	2737	19	2715	16	2684	26	2
29	109	57	0.48	13.550	0.245	0.5188	0.0064	0.68305	2737	22	2719	17	2694	27	2
40p *	204	347	0.57	45.146	5.923	1.7065	0.2112	0.94325	2758	70	3891	124	6418	484	−220
31kf *	403	587	0.62	38.739	5.941	1.4566	0.2193	0.98165	2767	47	3739	142	5794	551	−172
20 *	244	130	0.56	14.858	1.059	0.5330	0.0061	0.16092	2844	110	2806	66	2754	26	4

Notes: *Analyses are sorted from highest to lowest ^{207}Pb/^{206}Pb age.*

Grain characteristics: k = cracked; z = oscillatory zoning; f = fragment; p = patchy zonation; c = core; r - thin rim; u = homogeneous; U = high uranium (bright).

** Omitted because of high Sr and/or irregular profile.*

Error Corr. is correlation coefficients of X–Y errors on the concordia plot.

Disc. is percent discordance for the given ^{207}Pb/^{206}Pb age.

Relation between ages and concordia co-ordinates: $Y = {}^{206}Pb/{}^{238}U = EXP(L238\times(206\text{-}238Age)) - 1$; $X = {}^{207}Pb/{}^{235}U = EXP(L235\times(207\text{-}235Age)) - 1$.
^{207}Pb/^{206}Pb = 137.88 × X/Y; U decay constants (L238 & L235) from *Jaffey et al. (1971), where L238 = 1.55125 ×10^{10}/yr; L235 = 9.8485 ×10^{10}/yr.*

Table 5.2. Zircon U/Pb CA-ID-TIMS isotopic data from sample 20PMT001, quartz-feldspar porphyry intrusion, Hollinger pit, Timmins.

Analysis No. / Epoxy Mount	Weight (µg)	U (ppm)	Th/U	Pb_C (pg)	$^{206}Pb/^{204}Pb$ Measured	$^{207}Pb/^{235}U$	2σ	$^{206}Pb/^{238}U$	2σ	Error Corr.	$^{207}Pb/^{206}Pb$	2σ	$^{206}Pb/^{238}U$ Age	2σ	$^{207}Pb/^{235}U$ Age	2σ	$^{207}Pb/^{206}Pb$ Age	2σ	% Disc.
20PMT001: Quartz-feldspar porphyry intrusion, Hollinger pit, Tisdale Township (UTM 476638E 5368665N, NAD83, Zone 17)																			
Z1 / grain 24	~0.8	144	0.37	0.2	15853	12.958	0.041	0.5123	0.0015	0.938	0.18343	0.00020	2666.6	6.4	2676.6	3.0	2684.1	1.8	0.8
Z2 / grain 25	~0.8	85	0.32	0.2	11038	12.909	0.051	0.5113	0.0019	0.955	0.18313	0.00021	2662.0	8.3	2673.0	3.7	2681.4	1.9	0.9
Z3 / grain 28	~0.8	38	0.28	0.2	5795	12.856	0.059	0.5087	0.0022	0.961	0.18328	0.00023	2651.2	9.6	2669.1	4.3	2682.8	2.1	1.4
Z4 / grain 14	~0.8	67	0.33	0.3	5115	12.801	0.049	0.5047	0.0018	0.952	0.18397	0.00022	2633.8	7.8	2665.1	3.6	2689.0	2.0	2.5

Notes: *All zircon (z) grains have been thermally annealed and etched in HF (Mattinson 2005).*

Th/U calculated from radiogenic $^{208}Pb/^{206}Pb$ ratio and $^{207}Pb/^{206}Pb$ age assuming concordance.

Pb_C is total common Pb assuming the isotopic composition of laboratory blank:
assigned the isotopic composition of laboratory blank ($^{206}Pb/^{204}Pb$=18.49±0.4%; $^{207}Pb/^{204}Pb$=15.59±0.4%;$^{208}Pb/^{204}Pb$=39.36±0.4%).

$^{206}Pb/^{204}Pb$ corrected for fractionation and common Pb in the spike.

Pb/U ratios corrected for fractionation, common Pb in the spike, and blank.

Correction for ^{230}Th disequilibrium in $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ assuming Th/U of 4.2 in the magma.

Error Corr. is correlation coefficients of X–Y errors on the concordia plot.

Disc. is percent discordance for the given $^{207}Pb/^{206}Pb$ age.

Decay constants are those of Jaffey et al. (1971): ^{238}U and ^{235}U are 1.55125 ×10^{10}/yr and 9.8485 ×10^{10}/yr.

$^{238}U/^{235}U$ ratio of 137.88 used for $^{207}Pb/^{206}Pb$ model age calculations.

DISCUSSION

This new age determination of 2682.8±1.1 Ma for the porphyry intrusions of the Hollinger–McIntyre deposits suggests many previous published ages from the Timmins gold camp may be incorrect and should be re-examined. There are 8 porphyry intrusions located within or near the Hollinger–McIntyre gold deposit that plunge east-northeast and coalesce at depth (*see* Figure 5.1; Corfu et al. 1989; MacDonald, Piercey and Hamilton 2005). Numerous other porphyries throughout the camp have also been noted geochemically as comagmatic (MacDonald and Piercey 2019). This suggests that all age determinations on porphyry intrusions throughout the Timmins camp ranging from 2687 to 2691 Ma may need to be re-evaluated (Corfu et al. 1989; Gray and Hutchinson 2001; Ayer et al. 2005; MacDonald, Piercey and Hamilton 2005); with the exception of a porphyry intrusion in the Hoyle Pond Mine with an age of 2684.4±1.9 Ma (Bateman et al. 2005) that is within error of the new age.

The porphyry intrusions of the Timmins camp have been noted as the intrusive equivalent to the Krist formation metavolcanic rocks that occur at the base of the Porcupine basin based on lithogeochemistry and geochronology (MacDonald and Piercey 2019). The new age reported herein suggests previous age determinations for rocks of the Krist formation of 2687.3±1.6 and 2687.5±1.3 Ma (Ayer, Ketchum and Trowell 2002) may also need to be re-examined. If true, this also suggests the Porcupine metasedimentary rocks in the Timmins camp are younger than 2682.8 Ma. Structurally, the new age also implies D_2 deformation commenced after 2682 Ma, as the porphyry intrusions of the Timmins camp predate the D_2 deformation; and narrows the length of time the Timmins camp underwent deformation (Bateman, Ayer and Dubé 2008). The age does not necessarily question previous interpretations of gold mineralization in the Timmins camp, but does shorten the gap between porphyry intrusion emplacement and the time of mineralization.

ACKNOWLEDGMENTS

The authors are grateful to Chelsea Sutcliffe and Don Davis for LA-ICP–MS work. We appreciate the help of Chris Osiowy, Jason Rockell and Jeff Cormier, all of Newmont Porcupine, for sample acquisition. We would also like to thank OGS staff including Michael Easton, Evan Hastie and Sonia Préfontaine for project support; Pat Gervais for work on figures; and Monica Gaiswinkler Easton for editorial assistance.

REFERENCES

Ayer, J., Amelin, Y., Corfu, F., Kamo, S., Ketchum, J., Kwok, K. and Trowell, N. 2002. Evolution of the southern Abitibi greenstone belt based on U-Pb geochronology: Autochthonous volcanic construction followed by plutonism, regional deformation and sedimentation; Precambrian Research, v.115, p.63-95.

Ayer, J., Ketchum, J. and Trowell, N. 2002. New geochronological and Nd isotopic results from the Abitibi greenstone belt, with emphasis on timing and tectonic implications of Late Archean sedimentation and volcanism; *in* Summary of Field Work and Other Activities, 2002, Ontario Geological Survey, Open File Report 6100, p.5-1 to 5-16.

Ayer, J.A., Thurston, P.C., Bateman, R., Dubé, B., Gibson, H.L., Hamilton, M.A., Hathway, B., Hocker, S.M., Houlé, M., Hudak, G., Lafrance, B., Lesher, C.M., Isopolatov, V., MacDonald, P.J., Péloquin, A.S., Piercey, S.J., Reed, L.H. and Thompson, P.H. 2005. Overview of results from the Greenstone Architecture Project: Discover Abitibi Initiative; Ontario Geological Survey, Open File 6154, 146p.

Azadbakht, Z., Bennett, D., Maity, B.K., Bousquet, P., Daniels, C.M., Hinz, S.L.K., Morelli, E. and Dorland, G. 2022. Report of Activities 2021 Resident Geologist Program, Timmins Regional Resident Geologist Report: Timmins and Sault Ste. Marie Districts; Ontario Geological Survey, Open File Report 6384, 151p.

Bateman, R., Ayer, J.A., Barr, E., Dubé, B. and Hamilton, M.A. 2004. Discover Abitibi. Gold Subproject 1. Protracted structural evolution of the Timmins–Porcupine gold camp and the Porcupine–Destor deformation zone; *in* Summary of Field Work and Other Activities, 2004, Ontario Geological Survey, Open File 6145, p.41-1 to 41-10.

Bateman, R., Ayer, J.A. and Dubé, B. 2008. The Timmins–Porcupine gold camp, Ontario: Anatomy of an Archean greenstone belt and ontogeny of gold mineralization; Economic Geology, v.103, p.1285-1308.

Bateman, R., Ayer, J.A., Dubé, B. and Hamilton, M.A. 2005. The Timmins–Porcupine gold camp, northern Ontario: The anatomy of an Archaean greenstone belt and its gold mineralization. Discover Abitibi Initiative; Ontario Geological Survey, Open File 6158, 90p.

Burrows, A.G. 1925. The Porcupine gold area; Ontario Department of Mines, Annual Report, 1924, v.33, pt.2, p.1-84.

Corfu, F., Krogh, T.E., Kwok, Y.Y. and Jensen, L.S. 1989. U–Pb zircon geochronology in the southwestern Abitibi greenstone belt, Superior Province; Canadian Journal of Earth Sciences, v.26, p.1747-1763.

Davis, D.W. 2002. U-Pb geochronology of Archean metasediments in the Pontiac and Abitibi subprovinces, Quebec, constraints on timing, provenance and regional tectonics; Precambrian Research, v.115, p.97-117.

Dubé, B., Mercier-Langevin, P., Ayer, J., Atkinson, B. and Monecke, T. 2017. Orogenic greenstone-hosted quartz-carbonate gold deposits of the Timmins-Porcupine camp; *in* Archean base and precious metal deposits, southern Abitibi greenstone belt, Canada, Society of Economic Geologists, Reviews in Economic Geology, v.19, p.51-79.

Dubé, B., Mercier-Langevin, P., Ayer, J., Pilote, J-L. and Monecke, T. 2020. Gold deposits of the world-class Timmins-Porcupine camp, Abitibi greenstone belt, Canada; *in* Geology of the world's major gold deposits and provinces, Society of Economic Geologists, Special Publication No.23, p.53-80.

Ferguson, S.A. 1966. Tisdale Township, District of Cochrane; Ontario Department of Mines, Map 2075, scale 1:12 000.

Gerstenberger, H. and Haase, G. 1997. A highly effective emitter substance for mass spectrometric Pb isotope ratio determinations; Chemical Geology, v.136, p.309-312.

Gray, M.D. and Hutchinson, R.W. 2001. New evidence for multiple periods of gold emplacement in the Porcupine Mining District, Timmins area, Ontario, Canada; Economic Geology, v.96; p.453-475.

Hastie, E.C.G., Kontak, D.J., Lafrance, B., Petrus, J.A., Sharpe, R. and Fayek, M. 2022. Evaluating geochemical discriminants in Archean gold deposits: A Superior Province perspective with an emphasis on the Abitibi greenstone belt; Economic Geology. doi.org/10.5382/econgeo.4979

Ispolatov, V., Lafrance, B., Dubé, B., Creaser, R. and Hamilton, M. 2008. Geologic and structural setting of gold mineralization in the Kirkland Lake–Larder Lake gold belt, Ontario; Economic Geology, v.103, p.1309-1340.

Jaffey, A.H., Flynn, K.F., Glendenin, L.E., Bentley, W.C. and Essling, A.M. 1971. Precision measurement of half-lives and specific activities of ^{235}U and ^{238}U; Physical Review, v.4, p.1889-1906.

Kamo, S.L. 2022. Report on U-Pb ID-TIMS geochronology for the Ontario Geological Survey: Bedrock Mapping Projects, Ontario: 2021-2022; internal report for the Ontario Geological Survey, Jack Satterly Geochronology Laboratory, University of Toronto, Toronto, Ontario, 12p.

Krogh, T.E. 1973. A low contamination method for hydrothermal decomposition of zircon and extraction of U and Pb for isotopic age determinations; Geochimica et Cosmochimica Acta, v.37, p.485-494.

Ludwig, K.R. 2003. User's manual for Isoplot 3.00: A geochronological toolkit for Microsoft® Excel®; Berkeley Geochronology Center, Special Publication No. 4, 71p.

MacDonald, P.J., Hastie, E.C.G. and Davis, D.W. 2017. Preliminary geology of Osway and Huffman townships and parts of Eric, Fingal and Arbutus townships, southern Swayze area, Abitibi greenstone belt; Ontario Geological Survey, Open File Report 6333, p.7-1 to 7-13.

MacDonald, P.J., and Piercey, S.J. 2019. Geology, lithogeochemistry, and significance of porphyry intrusions associated with gold mineralization within the Timmins–Porcupine gold camp, Canada: Canadian Journal of Earth Sciences, v.56, p.399-418.

MacDonald, P.J., Piercey, S.J. and Hamilton, M.A. 2005. An integrated study of intrusive rocks spatially associated with gold and base metal mineralization in Abitibi greenstone belt, Timmins area and Clifford Township: Discover Abitibi Initiative; Ontario Geological Survey, Open File 6160, 190p.

Mattinson, J.M. 2005. Zircon U-Pb chemical abrasion ("CA-TIMS") method: Combined annealing and multi-step partial dissolution analysis for improved precision and accuracy of zircon ages; Chemical Geology, v.220, p.47-66.

Monecke, T., Mercier-Langevin, P., Dubé, B. and Frieman, B.M. 2017. Geology of the Abitibi greenstone belt; *in* Archean base and precious metal deposits, southern Abitibi greenstone belt, Canada; Reviews in Economic Geology, v.19, p.7-49.

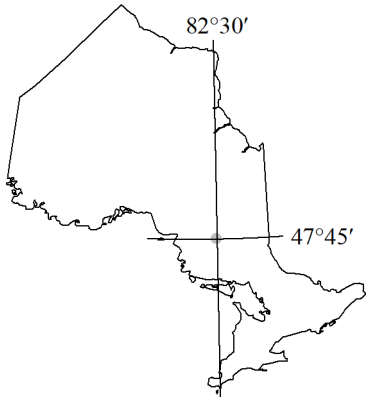
Robert, F. 2001. Syenite-associated disseminated gold deposits in the Abitibi greenstone belt, Canada; Mineralium Deposita, v.36, p.503-516.

Sutcliffe, C.N. 2021. U-Pb geochronology report for samples from Ontario by LA-ICPMS; internal report for the Ontario Geological Survey, Jack Satterly Geochronology Laboratory, University of Toronto, Toronto, Ontario, 75p.

Thurston, P.C., Ayer, J.A., Goutier, J. and Hamilton, M.A. 2008. Depositional gaps in Abitibi greenstone belt stratigraphy: A key to exploration for syngenetic mineralization; Economic Geology, v.103, p.1097-1134.

Tomlinson, K.Y., Davis, D.W., Stone, D. and Hart, T.R. 2003. U-Pb age and Nd isotopic evidence for crustal recycling and Archean terrane development in the south-central Wabigoon Subprovince, Canada; Contributions to Mineralogy and Petrology, v.144, p.684-702.

6. Project NE-22-003. Preliminary Geology and Mineral Potential of Dore and Swayze Townships and Part of Garnet Township, Swayze Area, Abitibi Greenstone Belt



T.P. Gemmell[1] and A. Buyers[2]

[1]Earth Resources and Geoscience Mapping Section, Ontario Geological Survey, Sudbury, Ontario P3E 6B5
[2]Department of Earth Sciences, Saint Mary's University, Halifax, Nova Scotia B3H 3C3

INTRODUCTION

The Swayze area of the Abitibi greenstone belt has long been considered the "poor cousin" to the neighboring Timmins, Matachewan and Kirkland Lake areas of the Abitibi greenstone belt and, therefore, has not received as much exploration attention. A regional-scale compilation mapping project in the mid-1990s (Heather 2001), which included widespread geochronological sampling, demonstrated that the Swayze area has the same episodic metavolcanic units and major faults as those found within the Abitibi greenstone belt east of the Kenogamissi Batholith (Figure 6.1; Heather 2001). The Swayze area should therefore represent a westward continuation of the fertile Abitibi greenstone belt and should have the potential to host the same types of precious and base metal mineral deposits.

This mapping project is part of a multi-year project that started in 2014 to update the geology and assess the mineral potential of the Swayze area (related project numbers: Project Unit 14-008, and projects NE-17-001, NE-17-002, NE-18-002 and NE-19-003). Field work this year focussed on Dore and Swayze townships and part of Garnet Township (*see* Figures 6.1 and 6.2). In addition, this year, a Bachelor of Science thesis project was supported by the Ontario Geological Survey for which the second author will study the melt inclusions in supracrustal rocks from the Blake River episode of the map area to determine the mineralization fertility and compare it to other parts of the Abitibi greenstone belt.

REGIONAL GEOLOGY

The Abitibi greenstone belt is located in the eastern part of the Wawa–Abitibi terrane of the southern Superior Province (Percival et al. 2006). It is composed predominantly of mafic to felsic metavolcanic rocks with minor ultramafic metavolcanic rocks, as well as clastic and chemical metasedimentary deposits. The volcanic and sedimentary episodes in the Abitibi greenstone belt are most recently defined by Thurston et al. (2008, and references therein) and Monecke et al. (2017, and references therein) and, for correlation purposes, the groups defined by Heather (2001) for the Swayze area are written in parenthesis following the episode name where applicable: pre-2750 Ma, 2750–2735 Ma Pacaud episode (Chester group), 2734–2724 Ma Deloro episode (Marion group), 2720–2710 Ma Kidd–Munro episode (Biscotasing group), 2710–2704 Ma Tisdale episode (Trailbreaker group) and the 2704–2695 Ma Blake River episode (Swayze group). Overlying the volcanic episodes in Ontario are 2 dominantly sedimentary episodes referred to the Porcupine-type (2690–2682 Ma) and the Timiskaming-type (2676–2670 Ma; Ridout group) sedimentary basins.

Summary of Field Work and Other Activities, 2022,
Ontario Geological Survey, Open File Report 6390, p.6-1 to 6-11.

© King's Printer for Ontario, 2022

The Swayze area (*see* Figure 6.1) of the Abitibi greenstone belt is mainly composed of mafic, intermediate and felsic metavolcanic rocks, with localized ultramafic metavolcanic rocks, clastic and chemical metasedimentary rocks and synvolcanic to syntectonic felsic to ultramafic intrusive rocks. It is bounded by the Kenogamissi Batholith (locally known as the Rice Lake batholith within the study area: *see* Becker and Benn (2003)) to the east, the Ramsey–Algoma granitoid complex to the south, the Kapuskasing Structural Zone to the west (*see* Figure 6.1) and the Nat River complex to the north (not labelled on Figure 6.1).

GEOLOGY OF DORE, SWAYZE AND PART OF GARNET TOWNSHIPS

The geology of Dore, Swayze and part of Garnet townships is composed of primarily metavolcanic rocks with local, but large-scale lenses and horizons of metasedimentary rocks (*see* Figure 6.2). The supracrustal rocks are also intruded and crosscut by smaller bodies of felsic to ultramafic intrusive rocks.

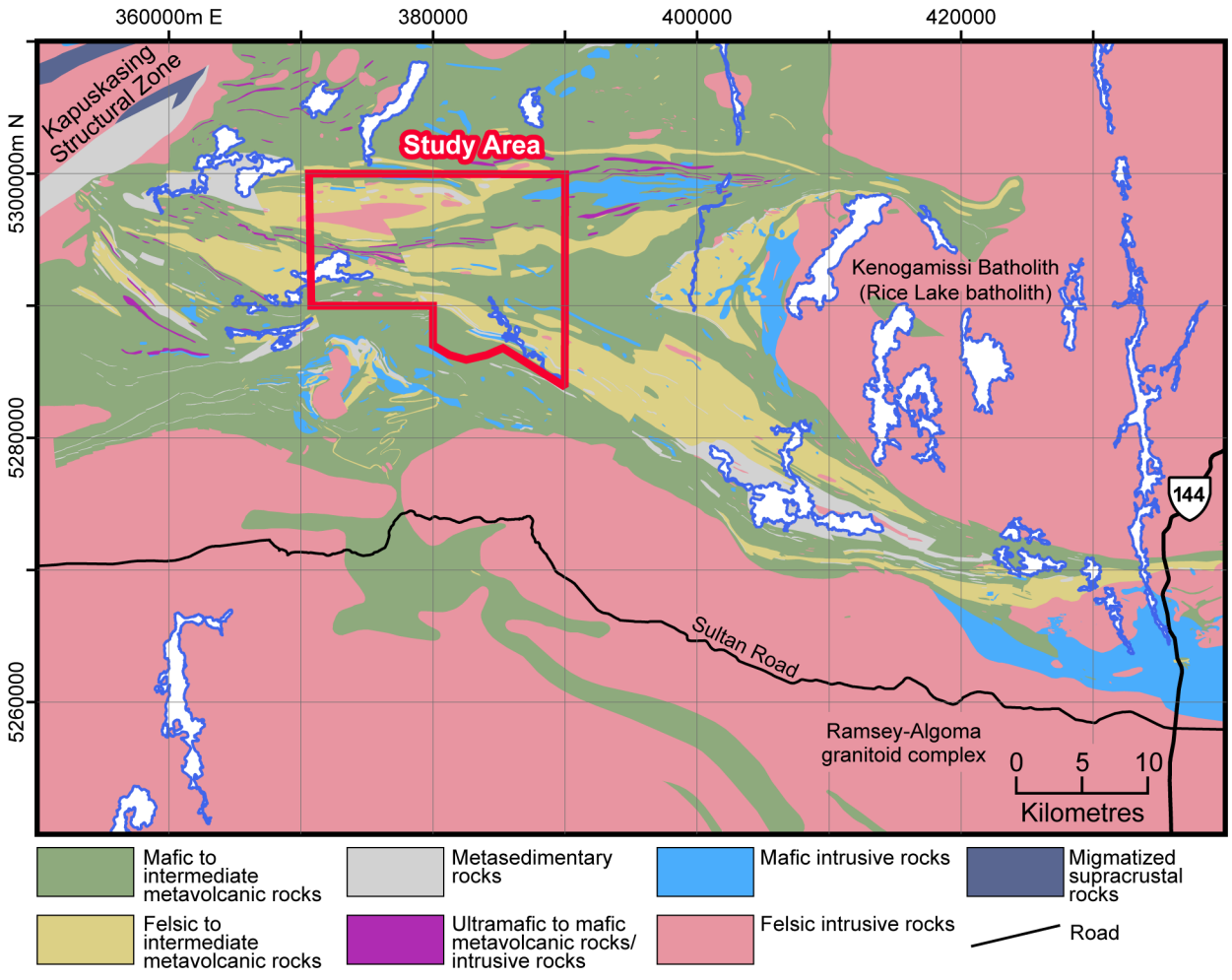


Figure 6.1. Simplified geological map of the southern Swayze area of the Abitibi greenstone belt displaying the study area (outlined by red box). Location information provided as Universal Transverse Mercator (UTM) co-ordinates using North American Datum 1983 (NAD83) in Zone 17. Geology *modified from* Ontario Geological Survey (2011).

Table 6.1. Geochronological data referred to in the text and shown on Figure 6.2.

Number	Zircon Method [a]	Age (Ma)	Interpretation	Rock Type	Easting [b] (m)	Northing [b] (m)	Source
1	U	2684.7 ±1.5	Emplacement	Quartz feldspar porphyry	378752	5299932	Kamo (2016)
2	U	2697.3 ±1.1	Volcanism	Reworked felsic metavolcanic rock	385429	5300013	Cattell, Krogh and Arndt (1984)
3	U	2696 ±2	Volcanism	Felsic metavolcanic rock	376609	5295234	van Breemen, Heather and Ayer (2006)
4	U	2700.3 ±1.9	Volcanism	Felsic metavolcanic flow	378672	5293593	Kamo (2018)

[a] *Methods abbreviations: U, U/Pb thermal ionization mass spectrometry.*
[b] *Locations provided as UTM co-ordinates in NAD83, Zone 17.*

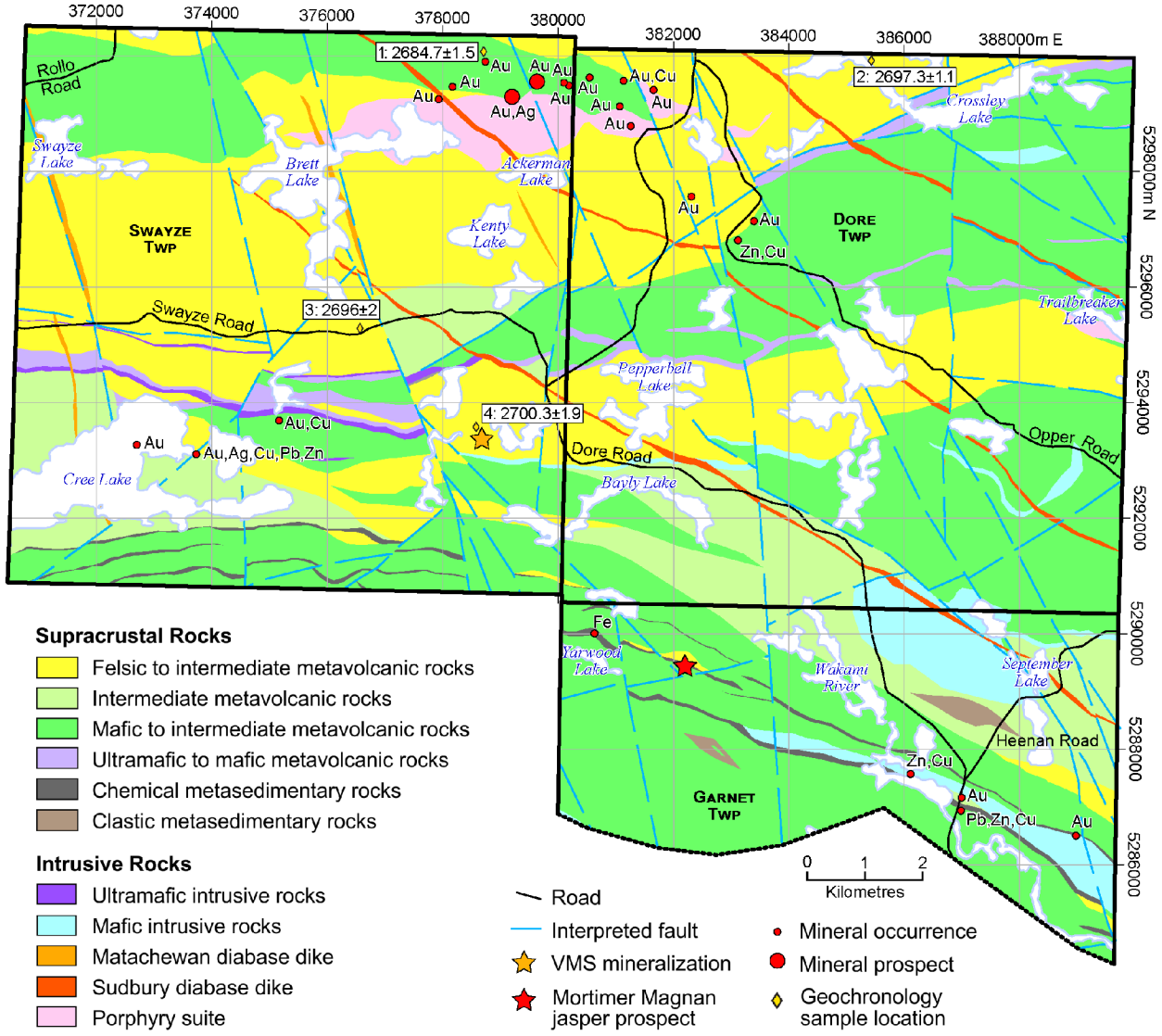


Figure 6.2. Preliminary geological map of Dore and Swayze townships and part of Garnet Township. Geochronology data are presented in million years (Ma); *see* Table 6.1 for additional information. Ontario Mineral Inventory (OMI) occurrences and prospects (Ontario Geological Survey 2022) indicate documented primary commodities. Abbreviations used: Ag, silver; Au, gold; Cu, copper; Fe, iron; Pb, lead; VMS, volcanogenic massive sulphide; Zn, zinc. Location information provided as UTM co-ordinates using NAD83 in Zone 17.

Archean Metavolcanic Rocks

The metavolcanic rocks of the study area include abundant mafic to intermediate massive to pillowed flows with minor felsic flows, abundant felsic to intermediate volcaniclastic with minor ultramafic to mafic flows.

Mafic to intermediate and intermediate metavolcanic rocks constitute a dominant lithology within Dore and Swayze townships and part of Garnet Township (*see* Figure 6.2). These metavolcanic rocks vary from dark green to light green and are typically cryptocrystalline to very fine-grained, massive and pillowed (locally variolitic) lava flows (Photo 6.1A). Pillows are typically ameboid shaped, range in size from 50 to 100 cm wide and have thin 1 to 3 cm interpillow material that locally contains pyrite or pyrrhotite. Massive fine-grained to locally coarse-grained ultramafic to mafic metavolcanic flows occur through central Dore Township and across the southern edge of Swayze Township (*see* Figure 6.2). These flows are typically 1 to 3 m thick and vary from moderate to dark green to an altered brown. Local polygonal jointed flows, spinifex (Photo 6.1B), breccias (Photo 6.1C) and cumulate facies were also observed in flow and shallow-level intrusions.

Felsic to intermediate metavolcanic rocks mainly occur as large volcanic piles in north to central Swayze Township extending across into Dore Township. The felsic to intermediate volcaniclastic rocks across central Swayze Township into Dore Township (Blake River episode; *see* Figure 6.2, Dore Township: 2697.3±1.1 Ma (geochronology location 2: Cattell, Krogh and Arndt 1984) and Swayze Township: 2696±2 Ma (geochronology location 3: van Breemen, Heather and Ayer 2006)) are dominantly white to light greyish green, but can be weathered to a brownish pink or turquoise blue. They are thinly bedded tuffs (Photo 6.1D), lapilli tuffs and tuff breccias (Photo 6.1E) with sparse lapillistones (Photo 6.1F). The felsic to intermediate coherent-flow rocks are commonly massive, white to light yellow grey with pink weathering and are commonly feldspar-phyric (lesser quartz-phyric) with 1 to 5 mm phenocrysts. The felsic to intermediate metavolcanic rocks across southern Dore Township into southeastern Swayze Township (Blake River episode; *see* Figure 6.2, 2700.3±1.9 Ma (geochronology location 4: Kamo 2018)) are dominantly white to light greyish green, thinly bedded tuffs and lapilli tuffs with sparse tuff breccias with minor coherent flows.

Archean Metasedimentary Rocks

The metasedimentary rocks in the study area (*see* Figure 6.2) primarily occur as chemical metasedimentary rocks (i.e., ironstone) in central Garnet and southern Swayze townships as thin (up to 100 m) laterally extensive units. Local, large-scale lenses of clastic metasedimentary rocks, dominantly pebble conglomerates, also occur across the study area (*see* Figure 6.2).

The ironstone in the map area primarily occurs in the central portion of Garnet Township and southern portion of Swayze Township. These ironstone units strike southeast, dip steeply southwest and have a strike length of approximately 15 km, extending into Cunningham and Benton townships to the west and east, respectively. They are primarily oxide facies with lesser sulphide facies. They are typically composed of alternating bands of chert, hematized chert (jasper; Photo 6.2A) and locally magnetite (Photo 6.2B). The units have a relatively continuous thickness of up to 100 m in Garnet Township, but are overthickened locally because of tight isoclinal folding. A sulphide-facies ironstone occurs locally at the stratigraphic base of the Mortimer Magnan jasper prospect (for location, *see* Figure 6.2; Gemmell and Mowbray 2017) and is composed of alternating bands of chert, pyrite and pyrrhotite and sparse sphalerite.

The conglomerate units occur in northeastern and northwestern Garnet Township as small sedimentary packages up to 400 m wide that generally trend to the southeast (*see* Figure 6.2). They are primarily matrix supported and are composed of pebble-size clasts with lesser cobbles and boulders intercalated with local silty to sandy beds (Photo 6.2C). The conglomerates are polymictic with clasts, in

decreasing order of abundance, of felsic to intermediate metavolcanic rocks, felsic to intermediate intrusive rocks, mafic metavolcanic rocks, massive pyrite and locally sparse chert.



Photo 6.1. Selected photographs of lithological units. **A**) Mafic pillowed flow in Dore Township (station 22AB095: 385255E 5292294N). **B**) Spinifex-textured ultramafic flow in Swayze Township (substation 22AB0068SS: 375944E 5294083N). **C**) Brecciated ultramafic flow in Swayze Township (substation 22AB0235SS: 371669E 5294800N). **D**) Felsic bedded tuff in Swayze Township (station 22TG066: 374841E 5298117N). **E**) Felsic to intermediate tuff breccia with plagioclase-phyric fragments in Swayze Township (substation 22AB0129SS: 373383E 5294635N). **F**) Felsic to intermediate lapillistone in Swayze Township (station 22AB058: 372085E 5295635N). Compass for scale is 22 cm long with sighting arm pointing north. All location information provided as UTM co-ordinates using NAD83 in Zone 17.



Photo 6.2. Selected photographs of lithological units. **A**) Jasper-bearing banded ironstone with a scour from overlying intermediate metavolcanic flow (station 22TG044: 382880E 5289001N). **B**) Folded magnetite-bearing banded ironstone in Garnet Township (station 22TG046: 383197E 5288375N). **C**) Deformed polymictic conglomerate with felsic to mafic metavolcanic, chert and massive sulphide clasts in Garnet Township (substation 22TG0205SS: 382710E 5287910N). **D**) Medium-grained gabbro with disseminated pyrite and pyrrhotite in Dore Township (station 22AB005: 388426E 5298444N). **E**) Peridotite with magnetite veins in Swayze Township (station 22TG051: 375963E 5293771N). **F**) Massive sulphide lens in Swayze Township (station 22AB130: 378631E 5293490N). Compass for scale is 22 cm long with sighting arm pointing north. Geotool handle for scale is 61 cm long. All location information provided as UTM co-ordinates using NAD83 in Zone 17.

Archean Intrusive Rocks

The Archean intrusive rocks in the map area are located throughout all 3 townships as mafic to ultramafic intrusions and as felsic porphyritic intrusions. Smaller gabbro intrusions of 2 Proterozoic dike swarms crosscut all rock types.

The northeastern margin of Dore Township contains the discontinuous extension (south of Crossley Lake, *see* Figure 6.2) of the Gowagamak gabbro which is predominantly found in Heenan Township (Heather 2001; Gemmell and Szumylo 2019), which is fine to medium grained and massive with little evidence of deformation (Photo 6.2D). The gabbros are spatially associated with mafic to ultramafic metavolcanic flows; however, contact relationships were not observed.

Several mafic to ultramafic intrusions (up to 1.5 km wide) occur across the study area. They are fine to medium grained, equigranular and with interlocking amphiboles, olivines, pyroxenes and plagioclase including secondary chlorite and/or magnetite (Photo 6.2E). These intrusions may locally represent synvolcanic intrusions.

The most significant porphyritic intrusion is located in northeastern Swayze Township stretching into northwestern Dore Township. It is typically felsic to intermediate with 1 to 5 mm feldspar phenocrysts with local 1 to 5 mm quartz phenocrysts. It is white to light grey, but can also be weathered to a brownish pink or turquoise blue. This unit is currently interpreted to be coeval with the surrounding felsic metavolcanic rocks.

Throughout the study area, there are also several small (metre to several hundreds of metres wide) felsic to intermediate porphyritic intrusions that are typically white to light grey and have 1 to 5 mm feldspar and/or quartz phenocrysts. One of these small intrusions in northeastern Swayze Township has an age of 2684.7±1.5 Ma (*see* Figure 6.2, geochronology location 1: Kamo 2016).

Proterozoic Intrusive Rocks

All Archean rocks in the field area are crosscut by 2 different Proterozoic dike swarms.

The generally north- to northwest–trending Matachewan gabbro dike swarm (*circa* 2460 Ma: Bleeker et al. 2015) is observed within the map area (*see* Figure 6.2). The dikes can range from centimetres to several metres wide, and typically exhibit well-developed chill margins. The amphibole- and pyroxene-rich Matachewan dikes are magnetic and locally contain euhedral to anhedral plagioclase phenocrysts.

The generally west-northwest–trending Sudbury gabbro dike swarm (1238±4 Ma: Krogh et al. 1987) is also observed within the map area (*see* Figure 6.2). These dikes have well-developed chill margins. The amphibole- and pyroxene-rich Sudbury dikes generally tend to be less magnetic than the gabbros of the Matachewan dike swarm.

STRUCTURAL GEOLOGY

The dominant fabric in the rocks in Swayze and Dore townships is a penetrative metamorphic foliation defined by sericite and chlorite that is approximately east trending and steeply dipping. The penetrative foliation rotates in western Garnet Township (south of the large ironstone; *see* Figure 6.2, chemical metasedimentary rocks) to trend approximately 110°, parallel to the dominant foliation observed in the rocks in Benton Township to the east (Gemmell and Szumylo 2019).

Locally, several high-strain zones (up to 50 m wide) parallel to the regional foliation have been observed predominantly north and south of the largest felsic volcanic package (central Swayze Township to northern Dore Township). These high-strain zones follow approximately the contacts between the felsic metavolcanic rocks and the intermediate to mafic metavolcanic rocks on either side. Another high-strain zone follows approximately the northern contact of the most southern ironstone in Garnet Township (*see* Figure 6.2). The high-strain zones are characterized by the destruction of primary textures and commonly contain abundant iron-carbonate alteration. They locally exhibit both sinistral and dextral kinematic indicators.

Evidence of folding was observed both at the outcrop scale (*see* Photo 6.2B) and at the map scale. Ultramafic metavolcanic rocks, observed in northeastern Dore Township and in southwestern Swayze Township, are interpreted to be the result of repetition. Similarly, the ironstone units in Garnet Township are also interpreted to be repeated by folding. The axial traces of these folds follow generally the regional foliation in the area. The exact location of these folds is still under investigation.

The study area has been crosscut by late north-northwest–trending brittle faults that exhibit both strike-slip and dip-slip components.

ALTERATION AND METAMORPHISM

The earliest alteration event is widespread vein-controlled replacement of amphiboles and feldspars by chlorite and sericite, respectively, in mafic to felsic metavolcanic rocks. Later phases of alteration overprinting the supracrustal rocks within high-strain zones include iron-carbonate, sericite, chlorite and quartz alteration, which is interpreted to be related to hydrothermal fluids.

Regional metamorphism in the area is typically lower greenschist facies, with locally observed upper greenschist facies. Lower greenschist facies assemblages are characterized by chlorite in the metavolcanic, metasedimentary and intrusive rocks. Upper greenschist facies metamorphism occurs within supracrustal rocks in proximity to the high-strain zones.

MINERALIZATION

Gold mineralization is the main commodity in the map area (*see* Figure 6.2). The gold mineralization is described, in the Ontario Mineral Inventory (Ontario Geological Survey 2022), as quartz-pyrite veins associated with iron-carbonate alteration. The most significant of which are the 2 gold mineral prospects in northeastern Swayze Township known as Kenty (northeast) and Kenty #1 shaft veins (northwest) (Ontario Geological Survey 2022). The veins are typically hosted within altered, intermediate to mafic, massive, pillowed and volcaniclastic rocks, as well as feldspar porphyry intrusions.

In addition to the gold occurrences, there are 3 significant known occurrences of base metal mineralization in the map area.

Volcanogenic massive sulphide mineralization was observed in southeastern Swayze Township (*see* Figure 6.2, orange star, stations 17BM053 and 22AB130, UTM 378631E 5293490N; *see also* Gemmell and Mowbray 2017) as an approximately 5 m wide rusted, highly strained zone of semi-massive to massive pyrite and pyrrhotite that is surrounded by favourable alteration packages of chlorite and/or sericite (up to 4367 ppm Zn and up to 293 ppm Cu: T.P. Gemmell, OGS, unpublished data, 2018, sample 17BM053) (Photo 6.2F). It is located within 80 m of a felsic to intermediate flow that has an emplacement age of 2700.3±1.9 Ma (Kamo 2018; *see* Figure 6.2, geochronology location 4). This area is being studied by the second author as part of a Bachelor of Science thesis project.

Sulphidized ironstone was also present at the northern margin of the Mortimer Magnan jasper project in Garnet Township (*see* Figure 6.2, red star; station 17TG130, UTM 382247E 5289506N) as semi-massive to massive pyrite and pyrrhotite (up to 488 ppm Cu and 1268 ppm Zn: T.P. Gemmell, OGS, unpublished data, 2018, sample 17TG130) that appears to partially replace relict oxide-facies ironstone. This area is still under study by the first author.

Blebs of sphalerite and chalcopyrite (up to 20 463 ppm Zn and 11 784 ppm Cu: T.P. Gemmell, OGS, unpublished data, 2018, station 17TG034, UTM 386298E 5287469N) up to 3 cm in size are found in quartz-carbonates veins (up to 10 cm) in Garnet Township along the shoreline of Wakami River (*see* Figure 6.2, location labelled as mineral occurrence "Zn,Cu"; Ontario Geological Survey 2022, MDI000000003176). These mineralized veins occur in a diorite body that is along strike with ironstone.

Felsic to intermediate metavolcaniclastic rocks across the area locally contain up to 10 cm clasts of massive pyrite and/or pyrrhotite that account for approximately 5 to 10% of the rock (Gemmell and Mowbray 2017). With volcanogenic massive sulphide–style mineralization already identified in the map area, the presence of primary massive sulphide fragments in the volcaniclastic rocks might indicate proximity to massive sulphide mineralization in the area.

ASSOCIATED THESIS PROJECT

A Bachelor of Science thesis project by the second author is planned to determine the chemistry of melt inclusions from supracrustal rocks within the Blake River volcanic episode (2704–2695 Ma; Thurston et al. 2008, and references therein; Monecke et al. 2017, and references therein) in Swayze and Dore townships and to compare those results to melt inclusion chemistry to Blake River volcanic episode rocks in other areas of the Abitibi greenstone belt, particularly the Doyon–Bousquet–LaRonde mining camp in Quebec. In 2022, 21 samples were collected from various volcanic units within the Blake River volcanic episode and other episodes that are under current investigation in the study area. Only a small subset of the samples will be analyzed for melt inclusion chemistry; however, low detection limit whole-rock geochemistry and petrographic analyses will be conducted for all samples. Melt inclusion work is being concentrated on rocks hosting the subeconomic volcanogenic massive sulphide–style massive sulphide lens in Blake River volcanic episode rocks located in Swayze Township (*see* Figure 6.2, orange star). The chemistry of the melt that formed the rocks hosting the subeconomic occurrence, along with detailed mapping of the mineralized area and geochemistry and petrographic work of the mineralized rock itself, will be used to characterize the occurrence and compare it to economic volcanogenic massive sulphide deposits elsewhere in the Abitibi greenstone belt where metamorphism, metasomatism, weathering, alteration and mineralization may have overprinted the primary chemical signature.

ACKNOWLEDGMENTS

This project has benefited from the advice and guidance of Sonia Préfontaine from the Ontario Geological Survey; Rasmus Haugaard from Metal Earth (Laurentian University); and the assistance of Ben Bates, Emilia Butty, Jonathan Enright and Sarah Mills (junior assistants). The authors are thankful to the staff of the Ontario Geological Survey, in particular Patrick Gervais for aiding with drafting figures, Shannon Evers and Jeremy Creppin for aiding in sample preparation, Monica Gaiswinkler Easton for editing, and Sheree Hinz of the Resident Geologists Office for help with the Ontario Mineral Inventory information. The authors also benefited from many discussions with, and comments from, Dr. Harold Gibson and Dr. Bruno Lafrance from Laurentian University (Harquail School of Earth Sciences). The authors would like to thank Brunswick House First Nation, Chapleau Cree First Nation, Flying Post First Nation and Mattagami First Nation for allowing the Ontario Geological Survey to map their traditional land use area.

The second author (AB) is undertaking a Bachelor of Science thesis project in the Department of Earth Sciences at Saint Mary's University under the supervision of Professor Jacob Hanley, with additional funding/support from a Natural Sciences and Engineering Research Council of Canada (NSERC) grant to Professor Hanley.

REFERENCES

Becker, J.K. and Benn, K. 2003. The Neoarchean Rice Lake batholith and its place in the tectonomagnetic evolution of the Swayze and Abitibi granite-greenstone belts, northeastern Ontario; Ontario Geological Survey, Open File Report 6105, 42p.

Bleeker, W., Kamo, S.L., Ames, D.E. and Davis, D. 2015. New field observations and U-Pb ages in the Sudbury area: Toward a detailed cross-section through the deformed Sudbury Structure; *in* Targeted Geoscience Initiative 4: Canadian Nickel-Copper-Platinum Group Elements-Chromium Ore Systems – Fertility, Pathfinders, New and Revised Models, Geological Survey of Canada, Open File 7856, p.151-156.

Cattell, A., Krogh, T.E. and Arndt, N.T. 1984. Conflicting Sm-Nd whole rock and U-Pb zircon ages for Archean lavas from Newton Township, Abitibi Belt, Ontario; Earth and Planetary Science Letters, v.70, p.280-290.

Gemmell, T.G. and Mowbray, A.B. 2017. Preliminary interpretation of the geology and base metal potential of the Doré Road–Foleyet Timber Road transect, Swayze area, Abitibi greenstone belt; *in* Summary of Field Work and Other Activities, 2017, Ontario Geological Survey, Open File Report 6333, p.8-1 to 8-13.

Gemmell, T.P. and Szumylo, N. 2019. Preliminary geology and mineral potential of Heenan and Benton townships and part of Esther Township, Swayze area, Abitibi greenstone belt; *in* Summary of Field Work and Other Activities, 2019, Ontario Geological Survey, Open File Report 6360, p.9-1 to 9-10.

Heather, K.B. 2001. The geological evolution of the Archean Swayze greenstone belt, Superior Province, Canada; unpublished PhD thesis, Keele University, Keele, England, 370p.

Kamo, S.L. 2016. Part A: Report on U-Pb ID-TIMS geochronology for the Ontario Geological Survey: Bedrock mapping projects, Ontario, Year 1: 2015–2016; internal report prepared for the Ontario Geological Survey, Jack Satterly Geochronology Laboratory, University of Toronto, Toronto, Ontario, 43p.

——— 2018. Part A: Report on U-Pb ID-TIMS geochronology for the Ontario Geological Survey: Bedrock mapping projects, Ontario, Year 3: 2017–2018; internal report prepared for the Ontario Geological Survey, Jack Satterly Geochronology Laboratory, University of Toronto, Toronto, Ontario, 9p.

Krogh, T.E., Corfu, F., Davis, D.W., Dunning, G.R., Heaman, L.M., Kamo, S.L., Machado, N., Greenhough, J.D. and Nakamura, E. 1987. Precise U-Pb isotopic ages of diabase dikes and mafic to ultramafic rocks using trace amounts of baddeleyite and zircon; *in* Mafic dike swarms, Geological Association of Canada, Special Paper 34, p.147-152.

Monecke, T., Mercier-Langevin, P., Dubé, B. and Frieman, B.M. 2017. Geology of the Abitibi greenstone belt; *in* Abitibi base and precious metal deposits, southern Abitibi greenstone belt, Canada, Society of Economic Geologists, Reviews in Economic Geology, v.19, p.7-49.

Ontario Geological Survey 2011. 1:250 000 scale bedrock geology of Ontario; Ontario Geological Survey, Miscellaneous Release—Data 126 – Revision 1.

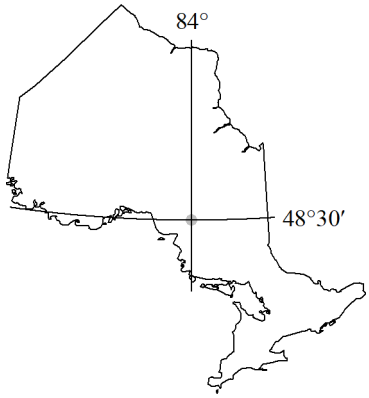
——— 2022. Ontario Mineral Inventory; Ontario Geological Survey, Ontario Mineral Inventory (November 2022 update), online database.

Percival, J.A., Sanborn-Barrie, M., Skulski, T., Stott, G.M., Helmstaedt, H. and White, D.J. 2006. Tectonic evolution of the western Superior Province from NATMAP and Lithoprobe studies; Canadian Journal of Earth Sciences, v.43, p.1085-1117.

Thurston, P.C., Ayer, J.A., Goutier, J. and Hamilton, M.A. 2008. Depositional gaps in Abitibi greenstone belt stratigraphy: A key to exploration for syngenetic mineralization; Economic Geology, v.103, p.1097-1134.

van Breemen, O., Heather, K.B. and Ayer, J.A. 2006. U-Pb geochronology of the Neoarchean Swayze sector of the southern Abitibi greenstone belt; *in* Geological Survey of Canada, Current Research 2006-F1, 32p.

7. Project NE-18-007. Preliminary Geology of Meath Township, Northeastern Michipicoten Greenstone Belt, Northeastern Ontario



L.E.D. Vice[1]

[1]Earth Resources and Geoscience Mapping Section, Ontario Geological Survey

INTRODUCTION

The multi-year project in the northeastern Michipicoten area was initiated to map the bedrock geology of 12 townships, including Marsh, Lang, Brackin, Rennie, Leeson, Stover, Copenace, Bruyere, West, Meath, Riggs and Glasgow townships (Figure 7.1). The objectives of the project are to 1) update and re-examine the bedrock geology maps in the area, 2) characterize the major rock units and stratigraphy and 3) evaluate the mineral potential of the area. During the summer of 2022, detailed bedrock geology mapping was completed in Meath Township (*see* Figure 7.1) and stratigraphically and structurally significant locations were visited throughout the belt as outlined in Vice, Perrouty and Robichaud (this volume). The preliminary geology of Meath Township is presented in this article (Figure 7.2). For information pertaining to the preliminary geology of previously mapped townships, please refer to Robichaud (2013), Robichaud and McDivitt (2014), Robichaud, McDivitt and Trevisan (2015), Robichaud et al. (2016), Walker and Robichaud (2016), Walker (2017) and Walker and Robichaud (2018).

REGIONAL GEOLOGY

The Michipicoten greenstone belt, located west of the Kapuskasing Structural Zone in the Wawa–Abitibi terrane of the southern Superior Province, consists of successions of Archean metavolcanic and metasedimentary rocks intruded by Archean intrusive rocks and crosscut by Proterozoic mafic dikes (Turek, Smith and Van Schmus 1982; Williams et al. 1991). The supracrustal rocks of the belt have been previously subdivided into 3 distinct volcanic cycles: 2900 Ma, 2750 Ma and 2700 Ma (Sage and Heather 1991; Heather and Arias 1992; Turek, Smith and Van Schmus 1982, 1984; Turek, Van Schmus and Sage 1988). Geochronological data from the northeastern Michipicoten greenstone belt project suggest that the volcanic history is more continuous than was previously interpreted, with supracrustal rock ages ranging from 2731 to 2695 Ma (Kamo 2014, 2015, 2016, 2019; Davis 2016), which are discussed further by Vice, Perrouty and Robichaud (this volume). Supracrustal rocks of the northeastern Michipicoten area are bounded by the Missinaibi Lake batholith to the east, the Ogasiwi Lake complex to the south, and the Wabatongushi Lake granitoid complex to the north (*see* Figure 7.1).

Summary of Field Work and Other Activities, 2022,
Ontario Geological Survey, Open File Report 6390, p.7-1 to 7-10.

© King's Printer for Ontario, 2022

GEOLOGY OF MEATH TOWNSHIP

The bedrock geology of Meath Township includes Archean supracrustal rocks bounded to the north by the Archean Wabatongushi Lake granitoid complex (*see* Figure 7.2). Supracrustal rocks are intruded by small bodies of Archean intrusive rocks and at least 2 generations of Proterozoic mafic dikes crosscut all Archean rocks (*see* Figure 7.2).

Supracrustal Rocks

Supracrustal rocks within Meath Township include mafic to ultramafic and felsic to intermediate metavolcanic rocks, as well as clastic and chemical metasedimentary rocks (*see* Figure 7.2). Metamorphism of the supracrustal rocks is primarily greenschist facies with a few exceptions mentioned below.

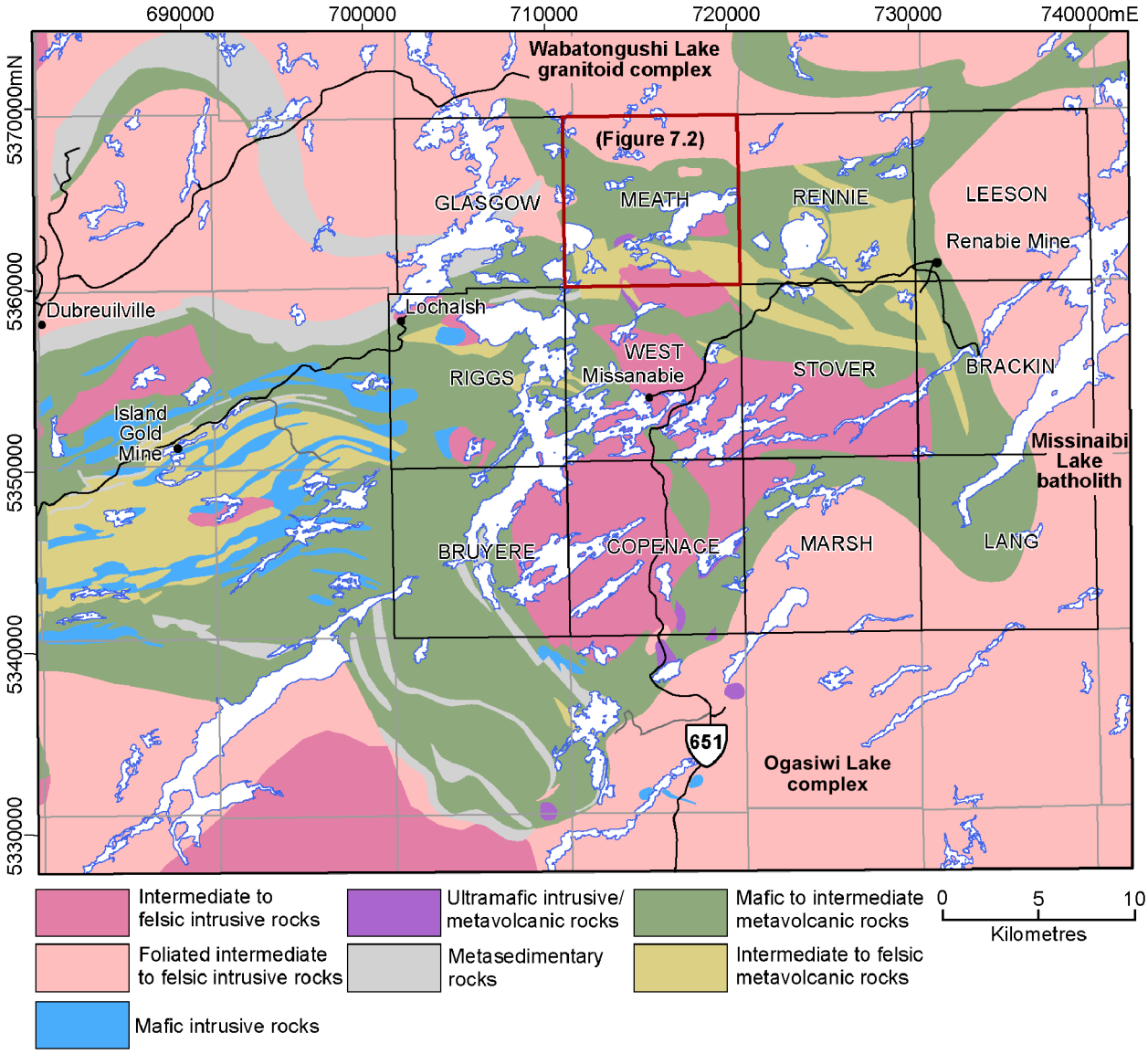


Figure 7.1. Simplified geological map of the northeastern Michipicoten greenstone belt displaying the locations of Meath Township (this year's study area) outlined in red and the other townships of this study outlined in black. Location information provided as Universal Transverse Mercator (UTM) co-ordinates using North American Datum 1983 (NAD83) in Zone 16 (geology *modified from* Ontario Geological Survey 2011b).

MAFIC TO ULTRAMAFIC METAVOLCANIC ROCKS

Mafic to ultramafic metavolcanic rocks south of Easey Lake are interlayered with felsic to intermediate metavolcanic rocks and metasedimentary rocks. These consist primarily of massive, fine-grained, chloritized flows, but locally appear as pillowed flows (Photo 7.1A). Individual least deformed

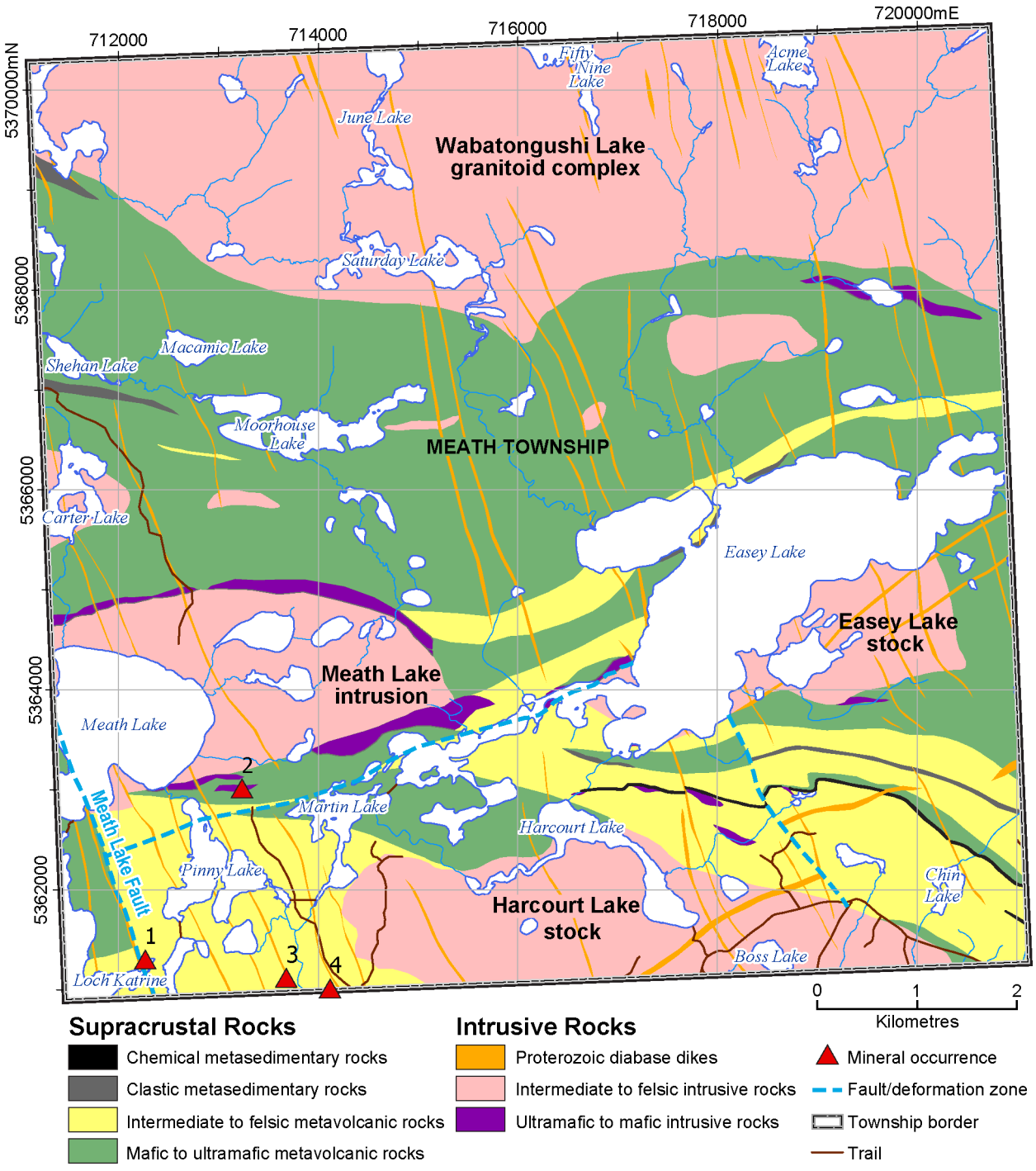


Figure 7.2. Preliminary geological map of Meath Township. Ontario Mineral Inventory (OMI) occurrences (Ontario Geological Survey 2022) are keyed to Table 7.1. Location information provided as UTM co-ordinates using NAD83 in Zone 16.

Table 7.1. Information about mineral occurrences in Meath Township (*from* Ontario Geological Survey 2022).

Number (shown in Figure 7.2)	Occurrence and OMI Number	Commodity*	Best Historical Value	Host Rock
1	E.S. Cascaden claims MDI42C08SE00022	Au	3050 ppb Au (grab sample)	Quartz veins within sheared porphyry (py-po)
2	Meath DDH M-82-1 MDI000000001609	Zn (Cu)	0.52 m @ 0.58% Zn, 0.1% Cu (DDH)	Graphitic metasedimentary rock intruded by porphyry and ultramafic rocks (py-po-cp)
3	Maisondor West MDI42C08SE00003	Au	0.94 m @ 2.98 oz/t Au (grab sample)	Quartz veins within silicified intermediate metavolcanic rock (py)
4	Maisondor showing 3 MDI42C08SE00082	Au	0.21 m @ 4.82 oz/ton Au (grab sample)	Felsic dikes intruding sheared intermediate volcanic rock (py-po)

** Commodities shown in parentheses, e.g., (Cu), indicate those commodities with grades below Ontario Minerals Inventory (OMI) cut-off grades (*from *Wilson et al. 2008).*

Abbreviations: *Au, gold; cp, chalcopyrite; Cu, copper; py, pyrite; po, pyrrhotite; Zn, zinc.*

pillows range from 10 to 30 cm long and 5 to 20 cm wide, with selvages and interpillow material ranging from 1 to 2 cm thickness. Spinifex texture is locally observed in thin flows northeast of Chin Lake and between Easey and Harcourt lakes (*see* Figure 7.2).

North and northwest of Easey Lake, mafic metavolcanic rocks are strongly foliated, chlorite altered and appear to increase in metamorphic facies (amphibolite facies) approaching Wabatonguishi Lake granitoid complex, which is most likely the result of a thermal aureole associated with this intrusion. Along the north shore of Easey Lake, the strongly deformed mafic metavolcanic rocks exhibit carbonate alteration related to shearing. Mafic metavolcanic rocks in this area are seen in gradational contact with clastic metasedimentary rocks (Photo 7.1B). Contact relationships with the Easey Lake stock, Meath Lake intrusion and the Wabatongushi Lake granitoid complex are uncertain because of poor exposure and access.

FELSIC TO INTERMEDIATE METAVOLCANIC ROCKS

A thick succession of felsic to intermediate metavolcanic rocks, located south of Easey Lake, consist of tuffs, crystal tuffs and tuff breccias and range from grey to pale white (Photo 7.1C). Crystal tuff layers are present north of the iron formation (*see* Figure 7.2) and contain quartz and feldspar crystals approximately 2 mm diameter. Tuffaceous layering is thickly laminated to thinly bedded (0.1–2 cm) with layers distinguished by colour, degree of chlorite alteration, grain size and relative abundance of quartz.

Felsic metavolcanic rocks to the north of Easey Lake are upper greenschist- to amphibolite-facies tuff and lapilli-tuff that host local sulphide lenses. These felsic metavolcanic rocks have a gradational contact with clastic metasedimentary rock where the felsic metavolcanic rocks contain garnet porphyroblasts up to 5 mm diameter. Additionally, silicified felsic metavolcanic rocks are interlayered with mafic metavolcanic rocks observed near Moorhouse Lake; however, poor access and limited exposure makes their extent north of Easey Lake difficult to distinguish.

CLASTIC METASEDIMENTARY ROCKS

Slivers of clastic metasedimentary rocks are found throughout Meath Township: in the southeast corner, along the north shore of Easey Lake, south of Shehan Lake and in the northwest corner toward the contact with the Wabatongushi Lake granitoid complex. The metasedimentary rocks are primarily composed of grey thinly to thickly laminated siltstone with local coarse-grained sandstone beds interbedded locally with either mafic or felsic metavolcanic rocks (*see* Photo 7.1B). Strong to intense deformation of these rocks makes younging direction difficult to determine; however, metasedimentary



Photo 7.1. Selected photographs of geological features within Meath Township. **A)** Pillowed mafic metavolcanic rock (station 22LEV038: UTM 715912E 5362701N). **B)** Contact between deformed metasedimentary rock and carbonate-altered mafic metavolcanic rock (station 22LEV110: UTM 711255E 5367015N). **C)** Felsic lapilli-tuff (station 22LEV052: UTM 718654E 5363177N). **D)** Chert-magnetite ironstone (station 22LEV095: UTM 717847E 5362973N). **E)** Sulphide-bearing Archean gabbro (station 22LEV107: UTM 717215E 5363445N). **F)** Massive ultramafic intrusive rock (station 22LEV125: UTM 717096E 5364349N). Compass for scale is 7.1 cm wide, with sighting arm pointing north. All UTM co-ordinates provided using NAD83 in Zone 16.

rocks observed in Rennie Township (*see* Figure 7.1), along strike to the metasedimentary rock located in southeast Meath Township, indicate younging to the northeast (Robichaud, McDivitt and Trevisan 2015). Conglomeratic metasedimentary rocks in northwest Stover Township (*see* Figure 7.1) along strike to those observed in southeast Meath Township suggests an age of 2695±3 Ma (*see* Vice, Perrouty and Robichaud, this volume, Figure 8.1; Davis 2016).

CHEMICAL METASEDIMENTARY ROCKS

Chemical metasedimentary rocks are observed in the southeast to south-central portion of Meath Township. Outcrops of these units are approximately 15 cm thick and consist of chert-magnetite layers interlayered with thin siltstone or sandstone laminations (0.1–1 cm; Photo 7.1D). The extent of the units is defined by high magnetic responses on the airborne geophysical surveys (OGS 1999, 2003, 2011a). Stratigraphically, these ironstones appear to define the boundary between 2 different metavolcanic packages.

Intrusive Rocks

Intrusive rocks within Meath Township include Archean mafic to ultramafic intrusions, Archean felsic to intermediate intrusions, including the Wabatongushi Lake granitoid complex, and Proterozoic diabase dikes.

ARCHEAN MAFIC TO ULTRAMAFIC INTRUSIVE ROCKS

Several small Archean gabbroic bodies intrude the supracrustal rocks south of Easey Lake (*see* Figure 7.2). These intrusions are magnetic, dark grey, medium grained, massive to weakly foliated, and are composed of equant crystals of amphibole with interstitial plagioclase and commonly contain up to 5% sulphide mineralization (Photo 7.1E). These gabbroic rocks intrude along the felsic to intermediate metavolcanic rocks and iron formation contact in central Meath Township.

Few outcrops of ultramafic intrusions occur at or near the contacts between the Meath Lake intrusion or Easey Lake stock and supracrustal rocks (*see* Figure 7.2), as well as locally near Moorhouse Lake (not shown in Figure 7.2). Additionally, an ultramafic intrusion is described in a discretionary asbestos occurrence (MDI42C08NE00002, not shown on map) northeast of Easey Lake near the contact with the Wabatongushi Lake granitoid complex. The extent of these units, including the area of the discretionary occurrence, is defined by a high magnetic response on the airborne geophysical survey (OGS 1999, 2003, 2011a). Ultramafic intrusive rocks observed are dark grey-green, massive, locally foliated, fine- to medium-grained peridotite with serpentine, magnetite, and local talc alteration, as well as local disseminated sulphide mineralization (Photo 7.1F). No age relationship is known for these intrusions.

ARCHEAN FELSIC TO INTERMEDIATE INTRUSIVE ROCKS

Archean felsic to intermediate intrusive rocks within Meath Township include the Wabatongushi Lake granitoid complex, the Harcourt Lake stock, the Easey Lake stock and the Meath Lake intrusion (*see* Figure 7.2), as well as small quartz-feldspar porphyry dikes and sills that intrude the supracrustal rocks.

The Wabatongushi Lake granitoid complex is composed of light pink to white, foliated, fine- to medium-grained biotite tonalite. Along the contact with supracrustal rocks these rocks display reddish pink hematite alteration and *lit-par-lit* relationships with metavolcanic rocks. In Rennie Township (*see* Figure 7.1), an age of 2700±1 Ma was determined for the Wabatongushi Lake granitoid complex (*see* Vice, Perrouty and Robichaud, this volume, Figure 8.1; Kamo 2016).

The Harcourt Lake stock is a massive, fine- to medium-grained hornblende granite. Along its contact, where visible, supracrustal rocks are intensely hematite altered with abundant quartz veining. In West Township, a U/Pb age of 2676±4 Ma was determined for this granitoid body (*see* Vice, Perrouty and Robichaud, this volume, Figure 8.1; Sutcliffe and Davis 2019).

Both the Easey Lake stock and the Meath Lake intrusion are poorly exposed and covered either by glacial till or lakes. Where exposed, both granitoid bodies are pink to reddish pink, massive to weakly foliated, medium-grained granite to granodiorite with local hematite alteration. The dominant mafic phase minerals in the Easey Lake stock and Meath Lake intrusion are biotite and hornblende, respectively. The extent of these intrusions is interpreted by aeromagnetic lows (OGS 1999, 2003, 2011a) and drilling results from Manitou Gold Inc. (Goudreau project, corporate presentation, manitougold.com/projects/goudreau-project/overview [accessed September 15, 2022]). Additional geochronological and geochemical analyses are necessary to better characterize these 2 intrusions.

PROTEROZOIC INTRUSIONS

Proterozoic mafic dikes, distinguished by sharp, linear aeromagnetic highs (Ontario Geological Survey 1999, 2003, 2011a), crosscut all Archean rocks in Meath Township. They are composed of magnetic, fine- to medium-grained gabbro containing plagioclase phenocrysts and local glomerocrysts up to 4 cm diameter. Most of these dikes trend north-northwest and are interpreted to be part of the Matachewan dike swarm (2460 Ma: Bleeker et al. 2015; Osmani 1991). The northeastern trending dikes are interpreted to be part of the Biscotasing dike swarm (*circa* 2170 Ma: Buchan, Mortensen and Card 1993).

STRUCTURAL GEOLOGY

The primary regional foliation in supracrustal rocks throughout Meath Township is parallel to bedding and varies in trend from northwest (~280°) to southwest (~240°), dips steeply north (~78–85°). Locally observed isoclinal folding of the supracrustal units suggest that bedding was overturned during this deformation event. Because the main foliation appears to follow the contacts with the Harcourt Lake stock, Easey Lake stock, the Meath Lake intrusion and the Wabatongushi Lake granitoid complex, deformation likely occurred prior to or during the emplacement of the granitoid bodies.

A significant deformation zone up to 500 m wide, consisting of local zones of high strain, extend along the southern contact of the Meath Lake intrusion and appears to continue along the northern contact of the Easey Lake stock. The continuation of this zone east is difficult to pinpoint because of poor access and exposure.

The Meath Lake fault in the southwestern corner of Meath Township appears to be a brittle–ductile feature that forms the western contact of the Meath Lake intrusion and offsets supracrustal rocks. Apparent dextral displacement is interpreted from offset of the granite–greenstone contact, which could indicate up to 7 km of horizontal displacement; however, the vertical component of this movement is unclear. Additional work planned in Glasgow Township is necessary to better understand this feature.

MINERALIZATION

Locations of notable mineral occurrences from Meath Township are shown in Figure 7.2 and details are summarized in Table 7.1. Potential targets for mineral exploration include structurally hosted gold mineralization, base metal volcanogenic massive sulphide (VMS) mineralization and magmatic nickel-copper-platinum group elements mineralization.

Gold mineralization is primarily associated with quartz veining, porphyry intrusions and silicified felsic to intermediate supracrustal rocks along shear zones in the southwest corner of the township (*see* Table 7.1: numbers 1, 3 and 4; *see also* Figure 7.2). There is also potential for structurally hosted gold mineralization in southeast Meath Township because it is a stratigraphic continuation of the volcanic packages southeast of Baltimore Lake, which host several gold occurrences in Stover Township (Robichaud et al. 2016; *see* Figure 7.1). Additionally, shear zones south of the Wabatongushi Lake granitoid complex are relatively unexplored and may also represent potential targets for gold exploration.

Base metal VMS mineralization has been observed in the felsic metavolcanic rocks of Stover Township (Robichaud et al. 2016; *see* Figure 7.1) that extend into the southern portion of Meath Township. In addition, the felsic metavolcanic rocks north of Easey Lake contain sulphide lenses and exhibit potential distal alteration (garnet) at amphibolite-grade metamorphism.

Serpentine-altered ultramafic intrusive rocks historically explored for asbestos are potential hosts for nickel-copper-PGE mineralization (Table 7.1: number 2). Several of the mafic to ultramafic intrusive rocks have disseminated sulphide mineralization. Anomalous nickel and cobalt concentrations from a recent drilling program in the township between the Meath Lake and Easey Lake intrusions (Manitou Gold Inc., news releases, June 13, and September 26, 2022), highlight the prospectivity of these rocks.

ACKNOWLEDGMENTS

This mapping project benefitted from the mapping assistance of Sara Craig and Aidan Papaioannou. Thanks to staff at the Ontario Geological Survey: Lise Robichaud and Sonia Préfontaine for guidance and support; Mathieu Levesque and Darla Bennett for community engagement; Patrick Gervais for aid drafting figures; Monica Gaiswinkler Easton for editorial assistance; Shannon Evers and Jeremy Creppin for aid in sample preparation. The author would like to thank Batchewana First Nation, Brunswick House First Nation, Chapleau Cree First Nation, Garden River First Nation, Michipicoten First Nation and Missanabie Cree First Nation for allowing the Ontario Geological Survey to map their traditional land use area. Special thanks to Rod, Kenny and Josée of Ernie's Campground and Cottages for their hospitality and flexibility over the summer.

REFERENCES

Bleeker, W., Kamo, S.L., Ames, D.E. and Davis, D.W. 2015. New field observations and U-Pb ages in the Sudbury area: Toward a detailed cross-section through the deformed Sudbury Structure; *in* Targeted Geoscience Initiative 4: Canadian Nickel-Copper-Platinum Group Elements-Chromium Ore Systems – Fertility, Pathfinders, New and Revised Models, Geological Survey of Canada, Open File 7856, p.151-156.

Buchan, K.L., Mortensen, J.K. and Card, K.D. 1993. Northeast-trending Early Proterozoic dykes of southern Superior Province: Multiple episodes of emplacement recognized from integrated paleomagnetism and U–Pb geochronology; Canadian Journal of Earth Sciences, v.30, p.1286-1296.

Davis, D.W. 2016. Geochronology of rocks from northwest Ontario 2015-16. Part 2: LA-ICP-MS Geochronology, internal report for the Ontario Geological Survey; Jack Satterly Geochronology Laboratory, University of Toronto, Toronto, Ontario, 100p.

Heather, K.B. and Arias, Z. 1992. Geological and structural setting of gold mineralization in the Goudreau–Lochalsh area, Wawa gold camp; Ontario Geological Survey, Open File Report 5832, 159p.

Kamo, S.L. 2014. Report on U-Pb CA-ID-TIMS geochronology on volcanic and plutonic rocks, Superior and Grenville provinces, Ontario; internal report for the Ontario Geological Survey, Jack Satterly Geochronology Laboratory, University of Toronto, Toronto, Ontario, 27p.

——— 2015. Report on U-Pb CA-ID-TIMS geochronology on volcanic and plutonic rocks, Superior and Grenville provinces, Ontario; internal report for the Ontario Geological Survey, Jack Satterly Geochronology Laboratory, University of Toronto, Toronto, Ontario, 27p.

——— 2016. Part A: Report on U-Pb ID-TIMS geochronology for the Ontario Geological Survey: Bedrock mapping projects, Ontario; internal report for the Ontario Geological Survey, Jack Satterly Geochronology Laboratory, University of Toronto, Toronto, Ontario, 48p.

——— 2019. Report on U-Pb ID-TIMS geochronology for the Ontario Geological Survey: Bedrock mapping projects, Ontario; internal report for the Ontario Geological Survey, Jack Satterly Geochronology Laboratory, University of Toronto, Toronto, Ontario, 26p.

Ontario Geological Survey 1999. Single master gravity and aeromagnetic data for Ontario, Geosoft® format; Ontario Geological Survey, Geophysical Data Set 1036.

——— 2003. Ontario airborne geophysical surveys, magnetic and electromagnetic data, grid and profile data (Geosoft® format), Wawa area; Ontario Geological Survey, Geophysical Data Set 1009b.

——— 2011a. Ontario airborne geophysical surveys, magnetic and electromagnetic data, grid and profile data (ASCII and Geosoft® formats) and vector data, Magpie River–Missinaibi Lake area—Purchased data; Ontario Geological Survey, Geophysical Data Set 1237.

——— 2011b. 1:250 000 scale bedrock geology of Ontario; Ontario Geological Survey, Miscellaneous Release—Data 126 – Revision 1.

——— 2022. Ontario Mineral Inventory; Ontario Geological Survey, Ontario Mineral Inventory (September 2022 update).

Osmani, I.A. 1991. Proterozoic mafic dike swarms in the Superior Province of Ontario; Chapter 17 *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, p.661-681.

Robichaud, L. 2013. Geology and mineral potential of Marsh and Lang townships, Michipicoten greenstone belt; *in* Summary of Field Work and Other Activities, 2013, Ontario Geological Survey, Open File Report 6290, p.3-1 to 3-10.

Robichaud, L. and McDivitt, J.A. 2014. Geology and mineral potential of Brackin Township, Michipicoten greenstone belt; *in* Summary of Field Work and Other Activities, 2014, Ontario Geological Survey, Open File Report 6300, p.5-1 to 5-11.

Robichaud, L., McDivitt, J.A. and Trevisan, B.E. 2015. Geology and mineral potential of Rennie and Leeson townships, Michipicoten greenstone belt; *in* Summary of Field Work and Other Activities, 2015, Ontario Geological Survey, Open File Report 6313, p.5-1 to 5-11.

Robichaud, L., Walker, J., West, S.M. and Nywening, A. 2016. Geology and mineral potential of Stover Township, Michipicoten greenstone belt; *in* Summary of Field Work and Other Activities, 2016, Ontario Geological Survey, Open File Report 6323, p.5-1 to 5-10.

Sage, R.P. and Heather, K.B. 1991. The structure, stratigraphy and mineral deposits of the Wawa area; Geological Association of Canada–Mineralogical Association of Canada–Society of Economic Geologists, Joint Annual Meeting, Toronto 1991, Field Trip A6, 118p.

Sutcliffe, C.N. and Davis, D.W. 2019. Part B: U–Pb geochronology by LA-ICPMS for samples from northern Ontario. Year 4: 2018–2019; internal report for the Ontario Geological Survey, Jack Satterly Geochronology Laboratory, University of Toronto, Toronto, Ontario, 146p.

Turek, A., Smith, P.E. and Van Schmus, W.R. 1982. Rb–Sr and U–Pb ages of volcanism and granite emplacement in the Michipicoten belt, Wawa, Ontario; Canadian Journal of Earth Sciences, v.19, p.1608-1626.

——— 1984. U–Pb zircon ages and the evolution of the Michipicoten plutonic–volcanic terrane of the Superior Province, Ontario; Canadian Journal of Earth Sciences, v.21, p.457-464.

Turek, A., Van Schmus, W.R. and Sage, R.P. 1988. Extended volcanism in the Michipicoten greenstone belt, Wawa, Ontario; abstract *in* Geological Association of Canada–Mineralogical Association of Canada, Joint Annual Meeting, St. John's 1988, Program with Abstracts, v.13, p.A127.

Walker, J. 2017. Geology and mineral potential of Bruyere Township, Michipicoten greenstone belt; *in* Summary of Field Work and Other Activities, 2017, Ontario Geological Survey, Open File Report 6333, p.6-1 to 6-10.

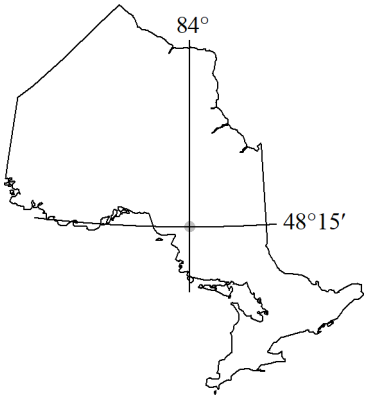
Walker, J. and Robichaud, L. 2016. Geology and mineral potential of Copenace Township, Michipicoten greenstone belt; *in* Summary of Field Work and Other Activities, 2016, Ontario Geological Survey, Open File Report 6323, p.6-1 to 6-9.

——— 2018. Geology and mineral potential of West Township, Michipicoten greenstone belt; *in* Summary of Field Work and Other Activities, 2018, Ontario Geological Survey, Open File Report 6350, p.5-1 to 5-10.

Williams, H.R., Scott, G.M., Heather, K.B., Muir, T.L. and Sage, R.P. 1991. Wawa Subprovince; Chapter 12 *in* Geology of Ontario, Ontario Geological Survey Special Volume 4, Part 1, p.485–539.

Wilson, A.C., Rowell, D.J., Seim, G.Wm. and Debicki, R.L. 2008. Procedural guidelines for provincially significant mineral potential mineral resource assessments; Ontario Geological Survey, Open File Report 6141, 91p.

8. Project NE-22-002. Introduction to a Geochronological and Structural Study of Supracrustal Assemblages in the Northeastern Michipicoten Greenstone Belt



L.E.D. Vice[1], S. Perrouty[2] and L. Robichaud[1]

[1]Earth Resources and Geoscience Mapping Section, Ontario Geological Survey, Sudbury, Ontario P3E 6B5
[2]Harquail School of Earth Sciences, Laurentian University, Sudbury, Ontario P3E 2C6

INTRODUCTION

This article introduces a PhD thesis study by the first author that commenced this 2022 field season, in partnership with the Metal Earth research program at Laurentian University, which is a complement to the ongoing bedrock geology mapping project of the northeastern Michipicoten greenstone belt (Vice, this volume). This project seeks to define the volcanic stratigraphy and structural evolution of the eastern Michipicoten greenstone belt by obtaining detailed geochronological, structural and lithogeochemical data to characterize the supracrustal assemblages and associated intrusions. A detailed characterization of the area will enable geological comparisons of the Michipicoten greenstone belt with adjacent age- and/or stratigraphic-equivalent greenstone belts in the Wawa, Abitibi and Wabigoon subprovinces.

In addition to the bedrock mapping of 12 townships planned for the multi-year Ontario Geological Survey (OGS) eastern Michipicoten bedrock geology mapping project led by the first author, this project will also include Dolson and Echum townships to the south, as shown in Figure 8.1.

GEOCHRONOLOGY OF THE NORTHEASTERN MICHIPICOTEN GREENSTONE BELT

The samples analyzed for geochronology throughout the northeastern Michipicoten greenstone belt are outlined in Figure 8.1 and Table 8.1. Intrabelt granitoid bodies are fairly well constrained with well-defined margins (Robichaud et al. 2015; Robichaud, McDivitt and Trevisan 2017; Walker and Robichaud 2018a, 2018b; Walker 2018; Robichaud and Walker 2019). Prior to the recent OGS mapping project, the Michipicoten greenstone belt was subdivided into 3 volcanic assemblages at 2900 Ma (Hawk assemblage), 2750 Ma (Wawa assemblage) and 2700 Ma (Catfish assemblage) (Sage and Heather 1991; Heather and Arias 1992; Turek, Smith and Van Schmus 1982, 1984; Turek, Van Schmus and Sage 1988). Recent OGS uranium–lead ages from the supracrustal rocks range from 2731 to 2695 Ma (*see* Figure 8.1; numbers 8, 12, 16, 22, 23) confirming the youngest ~2700 Ma episode, but also highlighting that volcanism in the region is more continuous than previously interpreted. This previously undocumented volcanism suggests that there could be up to an additional 3 volcanic episodes between 2750 and 2700 Ma. The extent, internal stratigraphy and boundaries of these volcanic episodes, synvolcanic intrusions and clastic and/or chemical metasedimentary rocks remain uncertain, highlighting the need for additional geochronological, detailed lithogeochemical and structural analyses of the region.

Summary of Field Work and Other Activities, 2022,
Ontario Geological Survey, Open File Report 6390, p.8-1 to 8-8.

© King's Printer for Ontario, 2022

Future Geochronological Work

Twenty-six samples were collected during the 2022 field season throughout the northern half of the study area (Figure 8.2; Table 8.2) from rock outcrops of primarily felsic metavolcanic and metasedimentary rocks to constrain the timing of volcanism and sedimentary deposition. Three samples of intrusive rocks were collected to better define the emplacement of these intrusions and timing of deformation. Geochronology samples will be analyzed at Laurentian University by split stream laser ablation inductively coupled plasma mass spectrometry (LA-ICP–MS) to obtain uranium–lead ages and associated trace element geochemistry of zircon.

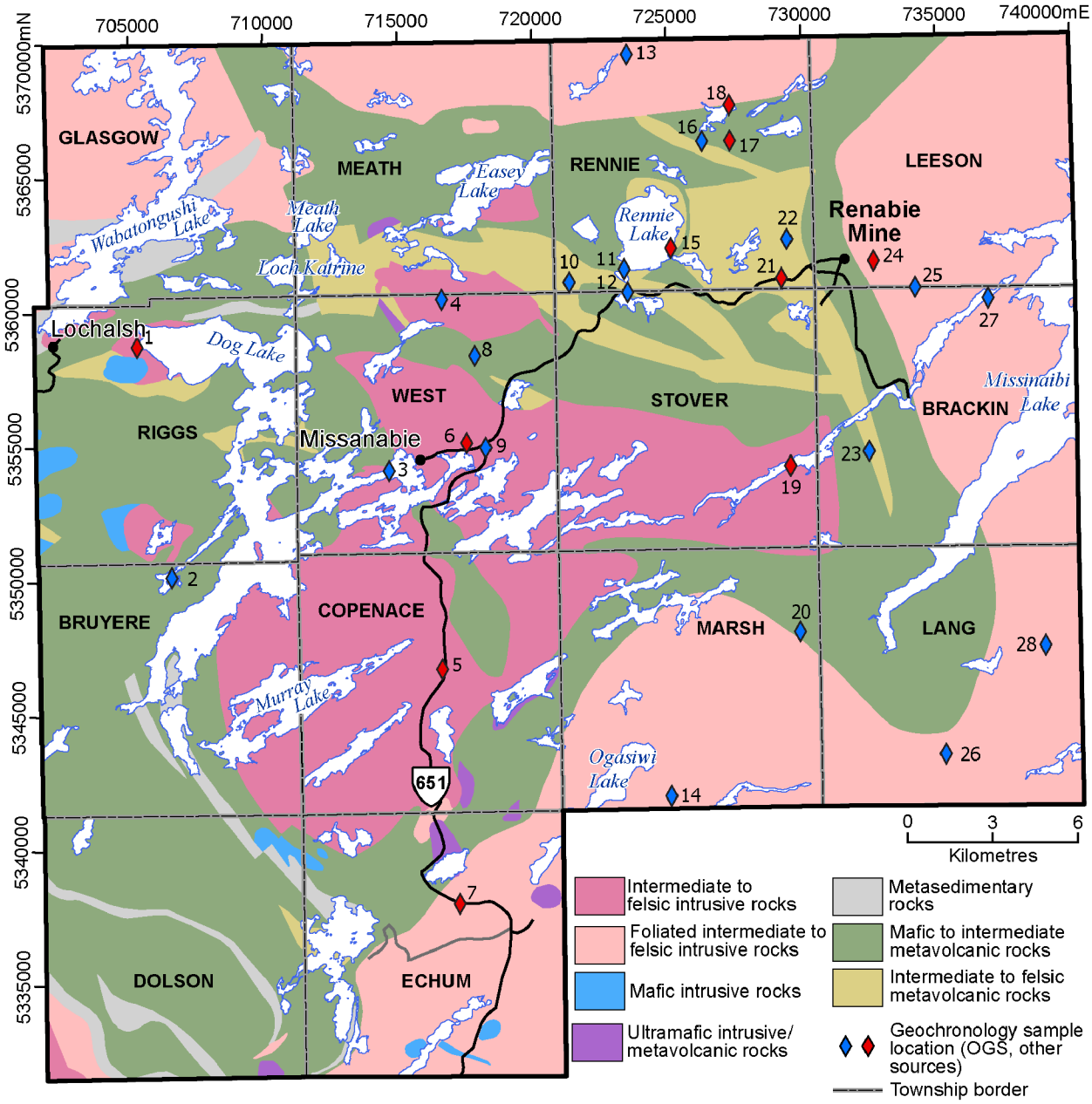


Figure 8.1. Simplified geological map of the northeastern Michipicoten greenstone belt displaying townships outlining the project area and sample locations for zircon U/Pb ages (keyed to Table 8.1). Location information provided as Universal Transverse Mercator (UTM) co-ordinates using North American Datum 1983 (NAD83) in Zone 16 (geology *modified from* Ontario Geological Survey 2011).

Table 8.1. Zircon uranium–lead geochronological results for samples from the northeastern Michipicoten greenstone belt.

Number (shown in Figure 8.1)	Sample No.	Rock Type	Age (Ma)	Method [a]	Interpretation	UTM Zone	Easting [b] (m)	Northing [b] (m)	Township	Source
1	1114, Lochalsh Bay stock	Granodiorite	2670±8	ID-TIMS	Emplacement	16	705633	5358864	Riggs	Turek et al. (1996)
2	17JW-160A	Felsic metavolcanic rock	Insufficient material to obtain age	ID-TIMS		16	707128	5350337	Bruyere	Davis, Ménard and Sutcliffe (2018)
3	18JW-529	Quartz-feldspar porphyry	2694±6 *(2725±5 inheritance)*	LA-ICP–MS	Emplacement	16	715101	5354512	West	Sutcliffe and Davis (2019)
4	18JW-534	Granite (Harcourt Lake stock)	2676±4 *(2697±4 inheritance)*	LA-ICP–MS	Emplacement	16	716903	5360919	West	Sutcliffe and Davis (2019)
5	Fe9-76	Granodiorite (Ash Lake pluton)	2684.5±2.7	ID-TIMS	Emplacement	16	717270	5347190	Copenace	Frarey and Krogh (1986)
6	78, Ash Lake pluton	Tonalite	2679±5	ID-TIMS	Emplacement	16	717957	5355614	West	Turek et al. 1996)
7	101, Hand Lake tonalite	Tonalite	2723±13 *(2711 minimum)*	ID-TIMS	Emplacement	16	718116	5338492	Echum	Turek et al. (1996)
8	18LR-017	Felsic metavolcanic rock	2718.8±2.2	CA-ID-TIMS	Volcanism	16	718184	5358867	West	Kamo (2019)
9	18JW-335B	Silicocarbonatite dike	1223±4	CA-ID-TIMS	Emplacement	16	718679	5355458	West	Kamo (2021)
10	15LR-234A	Sandstone	Insufficient material to obtain age	CA-ID-TIMS		17	277276	5361723	Rennie	Davis and Sutcliffe (2017)
11	15BT-038A	Granite (Rennie Lake stock)	2682±4	LA-ICP–MS	Emplacement	17	279347	5362099	Rennie	Davis (2016)
12	15LR-003A	Conglomerate	2695±3	LA-ICP–MS	Source population	17	279434	5361230	Rennie	Davis (2016)
13	15LR-163A	Tonalite (Wabatongushi Lake granitoid complex)	2700±1	CA-ID-TIMS	Emplacement	17	279864	5370062	Rennie	Kamo (2016)
14	13LR-066A	Tonalite (Missinaibi batholith)	2716±2	LA-ICP–MS	Emplacement	17	280059	5342459	Marsh	Petrus (2015)
15	113, Rennie Lake stock	Granodiorite	~2668 *(2670 minimum)*	ID-TIMS	Emplacement	17	281122	5362788	Rennie	Turek et al. (1996)

[a] ***Abbreviations:*** *(CA-)ID-TIMS = (chemical abrasion) isotope dilution thermal ionization mass spectrometry; LA-ICP–MS = laser ablation inductively coupled plasma mass spectrometry.*
[b] *Locations provided as UTM co-ordinates in NAD83.*

Table 8.1, ***continued***.

Number (shown in Figure 8.1)	Sample No.	Rock Type	Age (Ma)	Method [a]	Interpretation	UTM Zone	Easting [b] (m)	Northing [b] (m)	Township	Source
16	15LR-178A	Felsic metavolcanic rock	2704.6±2.1	CA-ID-TIMS	Volcanism	17	282487	5366689	Rennie	Kamo (2016)
17	103, Conboy Lake porphyry	Quartz-feldspar porphyry	2675±6 *(2672 minimum)*	ID-TIMS	Emplacement	17	283515	5366654	Rennie	Turek et al. (1996)
18	102, Conboy Lake tonalite	Tonalite	2688±14	ID-TIMS	Emplacement	17	283565	5367981	Rennie	Turek et al. (1996)
19	123, Ruby Lake stock	Granite	2661±11	ID-TIMS	Emplacement	17	285135	5354476	Stover	Turek et al. (1996)
20	13SP-003	Felsic metavolcanic rock	2723±5	ID-TIMS	Volcanism	17	285155	5348302	Marsh	Kamo (2014)
21	1164, Renabie crystal tuff	Felsic metavolcanic rock	2740±8	ID-TIMS	Volcanism	17	285170	5361459	Rennie	Turek et al. (1996)
22	15BT-036A	Felsic metavolcanic rock	2730.9±1.2	CA-ID-TIMS	Volcanism	17	285440	5362893	Rennie	Kamo (2016)
23	14LR-169	Felsic metavolcanic rock	2728.6±1.1	CA-ID-TIMS	Volcanism	17	288075	5354863	Brackin	Kamo (2015)
24	69, Nudulama tonalite	Tonalite	2741±21 *(2696 minimum)*	ID-TIMS	Emplacement	17	288607	5361917	Leeson	Turek et al. (1996)
25	14LR-183	Tonalite (Missinaibi batholith)	2720.8±1.4	CA-ID-TIMS	Emplacement	17	289642	5360791	Brackin	Kamo (2015)
26	13LR-224	Late granite stock	2666±2 *(2712±6; 2700±3 inheritance)*	ID-TIMS	Emplacement	17	290323	5343477	Lang	Kamo (2014)
27	14LR-111	Granodiorite (Missinaibi batholith)	2688±2 *(2716±2; 2694±2 inheritance)*	CA-ID-TIMS	Emplacement	17	292790	5360312	Brackin	Kamo (2015)
28	13LR-207	Tonalite (Missinaibi batholith)	2713.6±1.1	ID-TIMS	Emplacement	17	294251	5347320	Marsh	Kamo (2014)

[a] ***Abbreviations:*** *(CA-)ID-TIMS = (chemical abrasion) isotope dilution thermal ionization mass spectrometry; LA-ICP–MS = laser ablation inductively coupled plasma mass spectrometry.*
[b] *Locations provided as UTM co-ordinates in NAD83.*

Goals of upcoming field work are to better constrain the stratigraphy and provide geochronological constraints on supracrustal rocks to the west of the Meath Lake fault within Riggs, Dolson, Echum, Copenace and Bruyere townships (*see* Figures 8.1 and 8.2). Additionally, results from preliminary geochronological analyses will direct further targeted sampling and structural mapping throughout the study area.

Future Structural Work

Detailed structural mapping in key regions within the study area will be carried out in future field seasons to 1) identify and document the contact relationships between the main supracrustal assemblages, 2) investigate the nature and tectonic significance of major deformation zones and 3) provide a regional structural framework for known mineral resources, including volcanogenic massive sulphide, nickel-copper-platinum group element and orogenic gold occurrences, including the Renabie Mine (McDivitt et al. 2017, 2018, 2021).

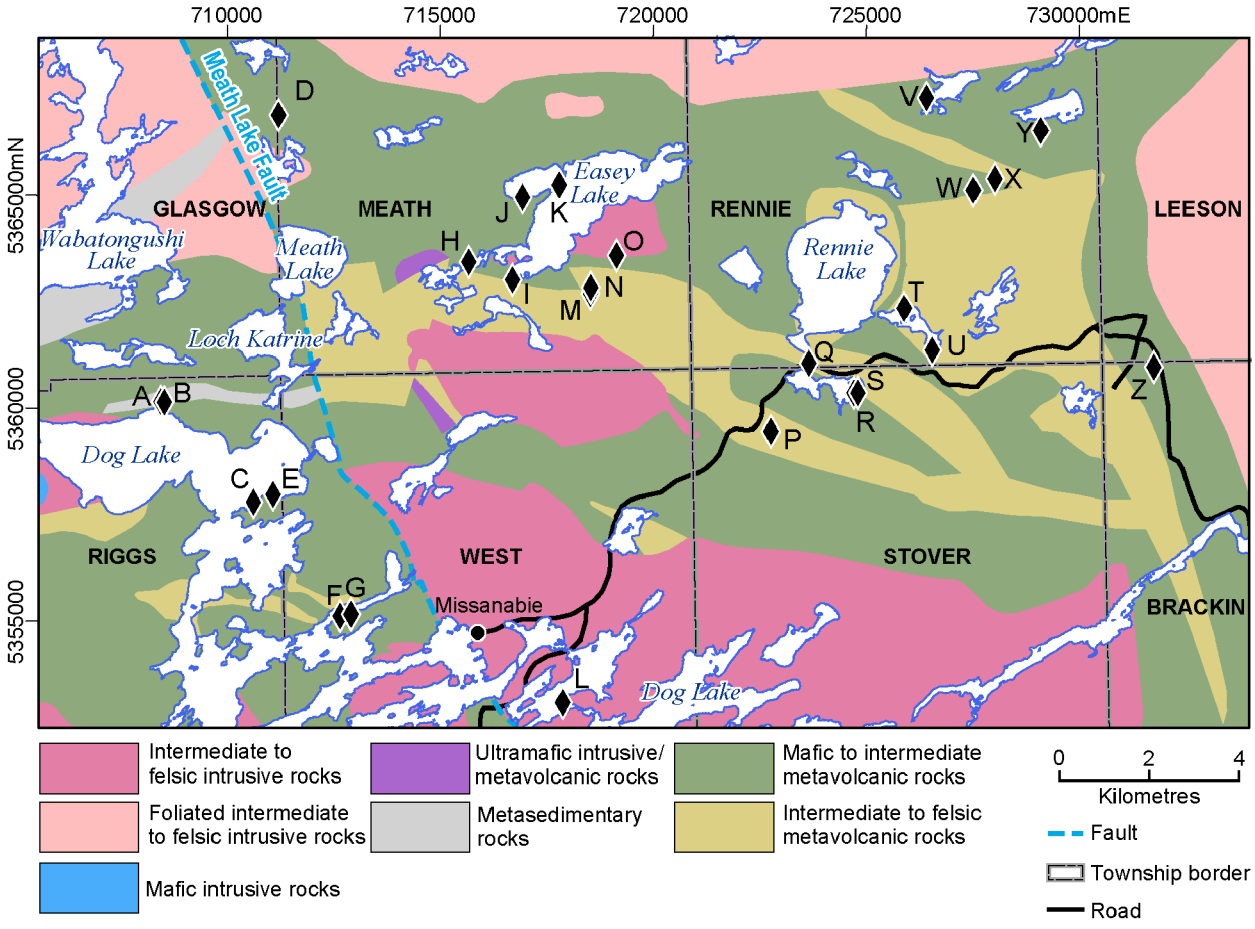


Figure 8.2. Sample locations for geochronology samples collected during the summer 2022 field season, represented by black diamonds; letters correspond to Table 8.2. Location information provided as UTM co-ordinates using NAD83 in Zone 16 (geology *modified from* Ontario Geological Survey 2011).

Table 8.2. Preliminary list of samples collected for geochronological analyses in the northeastern Michipicoten greenstone belt.

Letter (shown in Figure 8.2)	Station	Easting [a] (m)	Northing [a] (m)	Rock Type
A	22LEV069	708673	5360200	Muddy sandstone
B	22LEV069	708673	5360200	Felsic tuff
C	22LEV070	710876	5357917	Felsic tuff
D	22LEV110	711255	5367015	Sandy mudstone
E	22LEV074	711336	5358109	Sandy mudstone
F	22LEV073	712979	5355290	Felsic tuff
G	22LEV072	713230	5355338	Intermediate lapilli-tuff
H	22LEV079	715801	5363675	Felsic tuff
I	22LEV034	716832	5363280	Intermediate tuff
J	22LEV087	717024	5365221	Felsic tuff
K	22LEV097	717878	5365528	Muddy sandstone
L	22LEV143	718246	5353381	Quartz diorite
M	22LEV047	718671	5363002	Felsic tuff
N	22LEV051	718698	5363092	Felsic crystal tuff
O	22LEV055	719268	5363909	Alkali-feldspar granite
P	22LEV078	722982	5359865	Intermediate lapilli-tuff
Q	22LEV059	723838	5361485	Felsic tuff
R	22LEV064	724907	5360814	Sandy mudstone
S	22LEV064	724907	5360814	Felsic crystal tuff
T	22LEV061	726046	5362829	Felsic crystal tuff
U	22LEV062	726724	5361864	Felsic tuff
V	22LEV076	726447	5367782	Tuffaceous mudstone
W	22LEV066	727602	5365635	Felsic lapilli-tuff
X	22LEV067	728099	5365918	Foliated granodiorite
Y	22LEV068	729153	5367075	Felsic tuff
Z	22LEV077	731938	5361587	Felsic tuff

[a] *Locations provided as UTM co-ordinates in NAD83, Zone 16.*

ACKNOWLEDGMENTS

This work constitutes part of a PhD thesis study by the senior author in the Harquail School of Earth Sciences at Laurentian University. Thanks to the Ontario Geological Survey and Canada First Research Excellence Fund (CFREF) Metal Earth Program for their support. The authors thank Batchewana First Nation, Brunswick House First Nation, Chapleau Cree First Nation, Garden River First Nation, Michipicoten First Nation and Missanabie Cree First Nation for allowing the Ontario Geological Survey to map their traditional land use area. This is Metal Earth publication number MERC-ME-2022-32.

REFERENCES

Davis, D.W. 2016. Geochronology of rocks from northwest Ontario 2015-16. Part 2: LA-ICP-MS Geochronology, internal report for the Ontario Geological Survey; Jack Satterly Geochronology Laboratory, University of Toronto, Toronto, Ontario, 100p.

Davis, D.W., Ménard, J. and Sutcliffe, C.N. 2018. U-Pb geochronology of samples from northern Ontario. Part B: LA-ICPMS; internal report for the Ontario Geological Survey; Jack Satterly Geochronology Laboratory, University of Toronto, Toronto, Ontario, 94p.

Davis, D.W. and Sutcliffe, C.N. 2017. U-Pb geochronology by LA-ICPMS in samples from northern Ontario, internal report for the Ontario Geological Survey; Jack Satterly Geochronology Laboratory, University of Toronto, Toronto, Ontario, 131p.

Frarey, M.J. and Krogh, T.E. 1986. U-Pb zircon ages of late internal plutons of the Abitibi and eastern Wawa subprovinces, Ontario and Quebec; *in* Current Research, Part A, Geological Survey of Canada, Paper 86-1A, p.43-48.

Heather, K.B. and Arias, Z. 1992. Geological and structural setting of gold mineralization in the Goudreau–Lochalsh area, Wawa gold camp; Ontario Geological Survey, Open File Report 5832, 159p.

Kamo, S.L. 2014. Report on U-Pb CA-ID-TIMS geochronology on volcanic and plutonic rocks, Superior and Grenville provinces, Ontario; internal report for the Ontario Geological Survey, Jack Satterly Geochronology Laboratory, University of Toronto, Toronto, Ontario, 27p.

——— 2015. Report on U-Pb CA-ID-TIMS geochronology on volcanic and plutonic rocks, Superior and Grenville provinces, Ontario; internal report for the Ontario Geological Survey, Jack Satterly Geochronology Laboratory, University of Toronto, Toronto, Ontario, 27p.

——— 2016. Part A: Report on U-Pb ID-TIMS geochronology for the Ontario Geological Survey: Bedrock mapping projects, Ontario, internal report for the Ontario Geological Survey, Jack Satterly Geochronology Laboratory, University of Toronto, Toronto, Ontario, 48p.

——— 2019. Report on U-Pb ID-TIMS geochronology for the Ontario Geological Survey: Bedrock mapping projects, Ontario, internal report for the Ontario Geological Survey, Jack Satterly Geochronology Laboratory, University of Toronto, Toronto, Ontario, 26p.

——— 2021. Part A: Report on U-Pb ID-TIMS geochronology for the Ontario Geological Survey: Bedrock mapping projects, Ontario, internal report for the Ontario Geological Survey, Jack Satterly Geochronology Laboratory, University of Toronto, Toronto, Ontario, 14p.

McDivitt, J.A., Kontak, D.J., Lafrance, B., Petrus, J.A. and Fayek, M. 2021. A trace metal, stable isotope (H, O, S), and geochronological (U-Pb titanite) characterization of hybridized gold orebodies in the Missanabie–Renabie district, Wawa Subprovince (Canada); Mineralium Deposita, v.56, p.561-582.

McDivitt, J.A., Kontak, D.J., Lafrance, B. and Robichaud, L. 2018. Contrasting fluid chemistries, alteration characteristics, and metamorphic timing relationships recorded in hybridized orebodies of the Missanabie–Renabie gold district, Archean Wawa Subprovince, Ontario, Canada; Economic Geology, v.113, p.397-420.

McDivitt, J.A., Lafrance, B., Kontak, D.J. and Robichaud, L. 2017. The structural evolution of the Missanabie–Renabie gold district: Pre-orogenic veins in an orogenic gold setting and their influence on the formation of hybrid deposits; Economic Geology, v.112, p.1959-1975.

Ontario Geological Survey 2011. 1:250 000 scale bedrock geology of Ontario; Ontario Geological Survey, Miscellaneous Release—Data 126 – Revision 1.

Petrus, J.A. 2015. Report on U-Pb geochronology; internal report prepared for the Precambrian Geoscience Section, Ontario Geological Survey, by the Mineral Exploration Research Centre, Department of Earth Sciences, Laurentian University, 27p.

Robichaud, L., McDivitt, J.A. and Trevisan, B.E. 2017. Precambrian geology of Rennie and Leeson townships, Michipicoten greenstone belt; Ontario Geological Survey, Preliminary Map P.3803, scale 1:20 000.

Robichaud, L. and Walker, J. 2019. Precambrian geology of Stover Township, Michipicoten greenstone belt, northeastern Ontario; Ontario Geological Survey, Preliminary Map P.3828, scale 1:20 000.

Robichaud, L., Whitney, K.S., Munro, E. and Préfontaine, S. 2015. Precambrian geology of Marsh and Lang townships, Michipicoten greenstone belt; Ontario Geological Survey, Preliminary Map P.3787, scale 1:20 000.

Sage, R.P. and Heather, K.B. 1991. The structure, stratigraphy and mineral deposits of the Wawa area; Geological Association of Canada–Mineralogical Association of Canada–Society of Economic Geologists, Joint Annual Meeting, Toronto 1991, Field Trip A6, 118p.

Sutcliffe, C.N. and Davis, D.W. 2019. Part B: U–Pb geochronology by LA-ICPMS for samples from northern Ontario. Year 4: 2018–2019; internal report for the Ontario Geological Survey, Jack Satterly Geochronology Laboratory, University of Toronto, Toronto, Ontario, 146p.

Turek, A., Heather, K.B., Sage, R.P. and Van Schmus, W.R. 1996. U/Pb zircon ages for the Missanabie–Renabie area and their relation to the rest of the Michipicoten greenstone belt, Superior Province, Ontario, Canada; Precambrian Research, v.76, p.191-211.

Turek, A., Smith, P.E. and Van Schmus, W.R. 1982. Rb–Sr and U–Pb ages of volcanism and granite emplacement in the Michipicoten belt, Wawa, Ontario; Canadian Journal of Earth Sciences, v.19, p.1608-1626.

——— 1984. U–Pb zircon ages and the evolution of the Michipicoten plutonic–volcanic terrane of the Superior Province, Ontario; Canadian Journal of Earth Sciences, v.21, p.457-464.

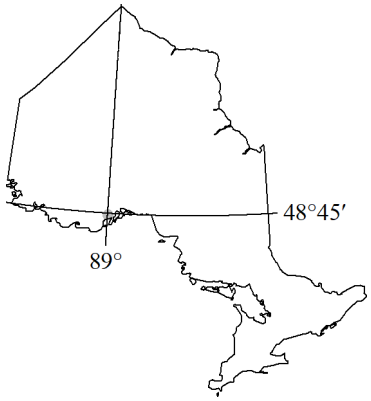
Turek, A., Van Schmus, W.R. and Sage, R.P. 1988. Extended volcanism in the Michipicoten greenstone belt, Wawa, Ontario; abstract, *in* Geological Association of Canada–Mineralogical Association of Canada, Joint Annual Meeting, St. John's 1988, Program with Abstracts, v.13, p.A127.

Walker, J. 2018. Precambrian geology of Bruyere Township, Michipicoten greenstone belt; Ontario Geological Survey, Preliminary Map P.3820, scale 1:20 000.

Walker, J. and Robichaud, L. 2018a. Precambrian geology of Copenace Township, Michipicoten greenstone belt; Ontario Geological Survey, Preliminary Map P.3814, 1:20 000.

——— 2018b. Geology and mineral potential of West Township, Michipicoten greenstone belt; *in* Summary of Field Work and Other Activities, 2018, Ontario Geological Survey, Open File Report 6350, p.5-1 to 5-10.

9. Project NW-19-001. Highlights of Bedrock Geology Mapping in the Quetico Subprovince, North of Thunder Bay, Northwestern Ontario



R.T. Metsaranta[1]

[1]Earth Resources and Geoscience Mapping Section, Ontario Geological Survey

INTRODUCTION

During the summer of 2022, field work was resumed on a project to produce 1:50 000 scale bedrock geology maps over a large area (herein referred to as the "project area") located north of the City of Thunder Bay. This area is mainly underlain by rocks of the Quetico Subprovince, Shebandowan greenstone belt and various Midcontinent Rift–related intrusive rocks (*see* Metsaranta 2015; Metsaranta and Walker 2019; Metsaranta and Hamilton 2020; Metsaranta and Kamo 2021). During 2022, field work was focussed on completing mapping of the southeastern part (herein referred to as the "map area") of the larger project area. Extensive new logging in the area carried out since the last field campaign in 2019 (*see* Metsaranta and Walker 2019) facilitated access to several previously unexamined areas. Figure 9.1 shows the map area and its simplified geology.

2022 FIELD WORK HIGHLIGHTS

The bulk of the 2022 map area was described by Metsaranta and Walker (2019). During the summer of 2022, field work was focussed on filling data gaps and mapping new or refurbished logging roads. This mainly led to better characterization of metaluminous syenitoid to granitoid intrusive complexes and peraluminous granite and granitic pegmatite units in the map area. In the southeastern part of the map area, a linear high magnetic anomaly (east-southeast trending, approximately 500 m wide and 2000 m long) seen on the airborne total magnetic field was investigated. Field investigation of this magnetic anomaly discovered a previously unrecognized mafic metavolcanic unit. The specific rock units upon which observations were made are described below.

Syenitoid to Granitoid Intrusive Complexes

Several Neoarchean intrusions and intrusive complexes composed primarily of metaluminous syenitoid to granitoid rocks occur within the map area (Metsaranta and Walker 2019; *see* Figure 9.1). These include the Mount Baldy intrusion, the Whitelily Lake intrusion, the Penassen Lakes intrusive complex, the Roll Lake intrusive complex and the Hades Lake intrusive complex. During 2022, additional mapping of the Hades Lake intrusive complex and the Roll Lake intrusive complex were carried out.

Hades Lake Intrusive Complex

The Hades Lake intrusive complex (HLIC) occurs in the eastern part of the map area. The HLIC, is unique amongst intrusive rocks of the map area, in that it contains a component of layered alkaline rocks.

Summary of Field Work and Other Activities, 2022,
Ontario Geological Survey, Open File Report 6390, p.9-1 to 9-9.

© King's Printer for Ontario, 2022

The general shape of the HLIC is defined by an ovoid normal high magnetic anomaly approximately 3.5 km long and 2 km wide. Where mapped by outcrop observations, the contacts of the complex do not perfectly correspond to the geophysical boundaries (i.e., magnetic). Detailed mapping of the intrusive body has not been carried out; however, observed outcrops indicate that the complex consists of at least 4 different phases based on crosscutting relationships. The earliest phase consists of layered hornblende melanogabbro, hornblende gabbro (Photo 9.1A) and monzogabbro or monzodiorite. The early mafic phase

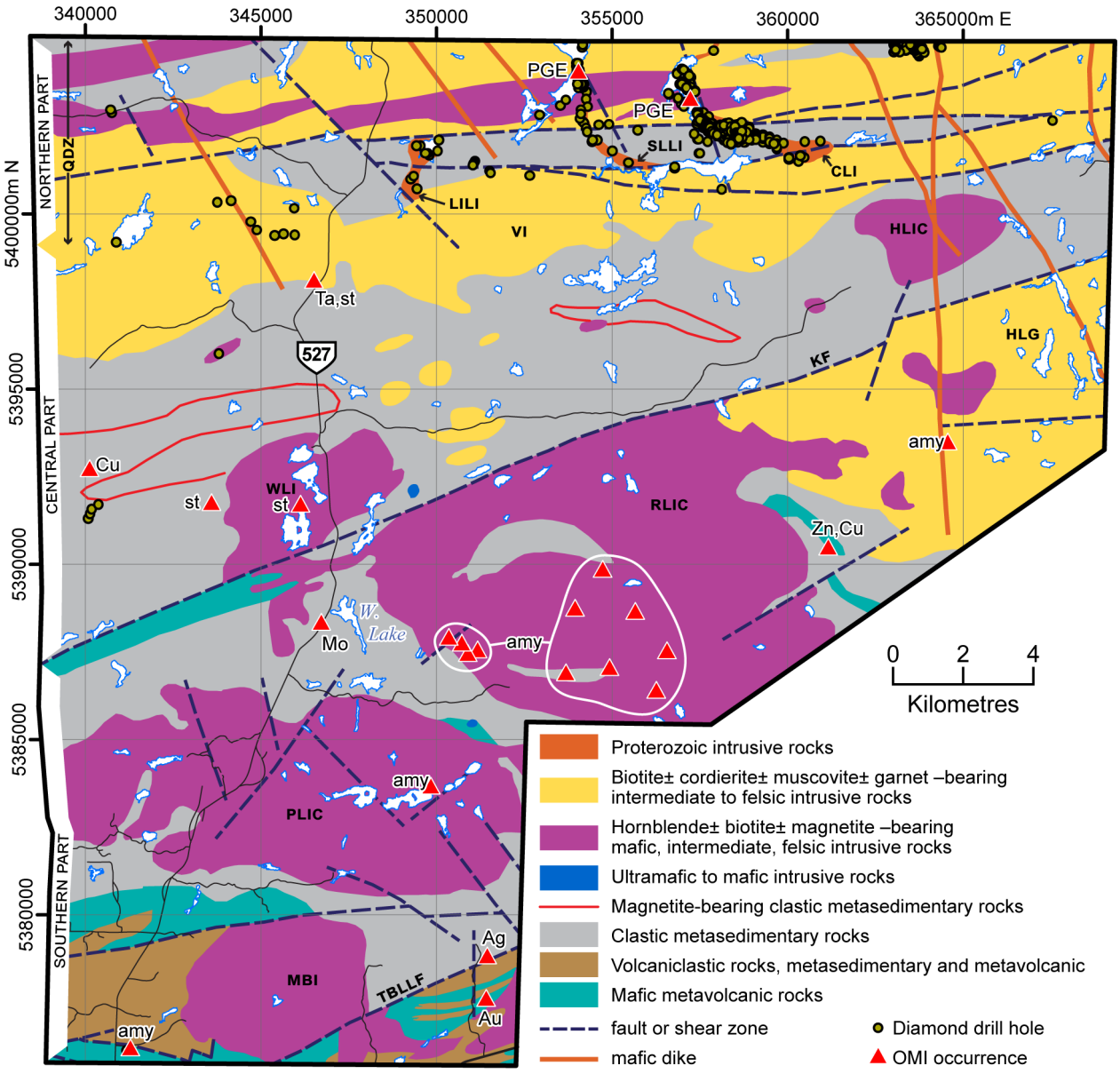


Figure 9.1. Simplified geology of the map area (*modified from* Metsaranta and Walker 2019). Geological abbreviations: CLI, Current Lake intrusive complex; HLG, Hilma Lake granite; HLIC, Hades Lake intrusive complex; KF, Kingfisher fault; LILI, Lone Island Lake intrusive complex; MBI, Mount Baldy intrusion; PLIC, Penassen Lakes intrusive complex; QDZ, Quetico deformation zone; RLIC, Roll Lake intrusive complex; SLLI, Steepledge Lake intrusive complex; TBLLF, Thunder Bay–Loon Lake fault; VI, Voutilainen intrusion; WLI, Whitelily Lake intrusion. Commodity (OMI) abbreviations: Ag, silver; amy, amethyst; Au, gold; Cu, copper; Mo, molybdenum; PGE, platinum group elements; st, granite building stone; Ta, tantalum; Zn, zinc. Other abbreviation: W.Lake, Walkinshaw Lake. Universal Transverse Mercator (UTM) co-ordinates provided using North American Datum 1983 (NAD83) in Zone 16. Mineral occurrences are *from* OGS (2019a). Drill-hole locations *from* Ontario Geological Survey (2019b).

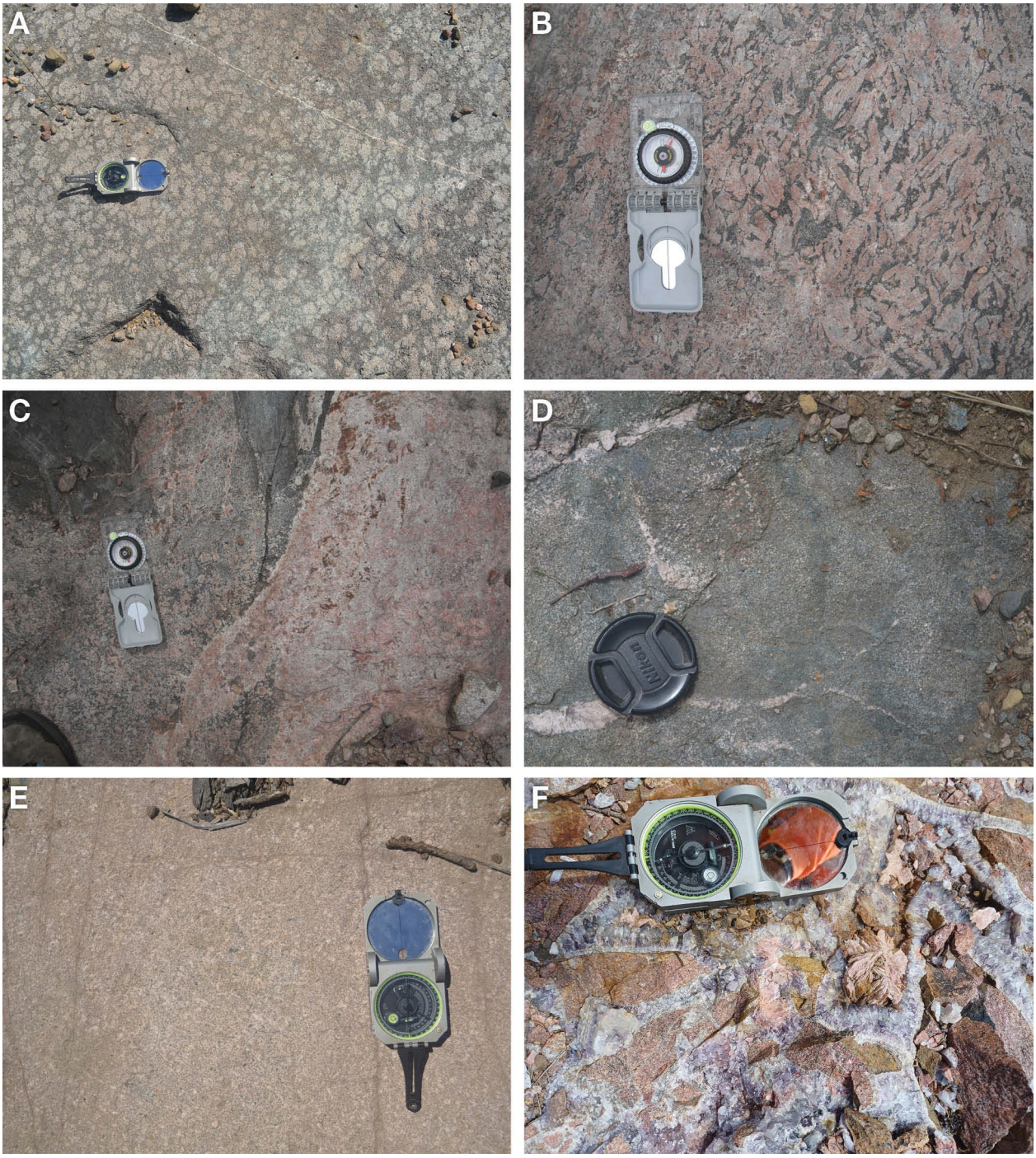


Photo 9.1. Representative photos of the Hades Lake and Roll Lake intrusive complexes. Photo locations are given as UTM co-ordinates using NAD83 in Zone 16. **A**) Coarse-grained poikilitic(?) gabbro phase of the Hades Lake intrusive complex; compass for scale is 22 cm in length (UTM 364843E 5399954N). **B**) Perthitic feldspar phenocryst–rich hornblende syenitic phase of the Hades Lake intrusive complex; compass for scale is 15 cm in length (UTM 365325E 5400279N). **C**) Late coarse-grained syenogranite phase of the Hades Lake intrusive complex crosscutting hornblende syenite and gabbro; compass for scale is 15 cm in length (UTM 365325E 5400279N). **D**) Medium-grained hornblende gabbro from the Roll Lake intrusive complex; lens cap for scale is 5 cm in diameter (UTM 352691E 5386807N). **E**) Homogenous porphyritic quartz monzonite from the Roll Lake intrusive complex; compass for scale is 22 cm in length (UTM 351906E 5387988N). **F**) Amethyst-barite breccia vein cutting medium-grained granodiorite to granite of the Roll Lake intrusive complex; compass for scale is 22 cm in length (UTM 355630E 5388524N).

is cut by, or possibly intercalated with, a distinctive alkali-feldspar (perthitic) porphyritic hornblende syenite (Photo 9.1B). A volumetrically dominant pink leucocratic to mesocratic biotite-hornblende granite postdates the syenite and appears to form the bulk of the complex (Photo 9.1C). The dominant granitic phase is intruded locally by a pegmatitic granite that forms a volumetrically minor fourth phase. Overall, the intrusion is weakly deformed, but local zones of stronger foliation indicate that the complex is likely Archean. Rocks of the HLIC clearly intruded deformed metasedimentary rocks; however, its relationship to the peraluminous granitoids and granitic pegmatites in the map area is equivocal. A sample of the alkalic feldspar porphyritic syenitic phase was collected for U/Pb geochronology. Preliminary geochemical data indicate that rocks of the HLIC and possibly related smaller alkalic felsic to intermediate intrusions in the map area are strongly enriched in light rare earth elements (e.g., La, Ce, Nd) and high field strength elements (e.g., Zr).

The HLIC appears to be similar to alkalic complexes found farther west in the Quetico Subprovince (*see* Lassen 2004) and, if this is confirmed by geochronology and further petrographic and geochemical data, it is the easternmost known example of this type of alkalic intrusive complex in the Quetico Subprovince.

Roll Lake Intrusive Complex

The Roll Lake intrusive complex (RLIC) is a large ovoid batholith-scale body that is similar in size and composition to the Penassen Lakes intrusive complex which is located to the southwest (*see* Figure 9.1; Metsaranta 2015; Metsaranta and Walker 2019). The long axis of the RLIC extends approximately 15 km east to west and its short axis extends approximately 8 km north to south. The RLIC and Penassen Lakes intrusive complex are similar to the HLIC in terms of the rock types they contain. However, igneous layering and the porphyritic hornblende syenite phase is thus far unique to the HLIC.

Locally, an early mafic phase of the RLIC is present, typically as autoliths within younger phases. Mafic to ultramafic phases include hornblendite, hornblende gabbro, and monzogabbro and/or monzodiorite (Photo 9.1D). The bulk of the RLIC consists of rocks that range from granodiorite to quartz monzonite (Photo 9.1E). Irregular contacts without chilled margins between mafic phases of the intrusion and intermediate age phases of the intrusion suggest that they are essentially coeval. Dikes, sills and pod-like pink biotite and hornblende granite also form a significant proportion of the RLIC; locally, these have sharp, planar contacts with older phases. Within the interior of the RLIC discontinuous zones of pillowed mafic metavolcanic rocks and polydeformed wacke locally containing dikes and sills of peraluminous granite suggest that supracrustal rocks and granitoids of these compositions formed the roof of the batholith when its phases were emplaced. A sample of pink to red, foliated, medium-grained biotite granodiorite was collected from the eastern part of the RLIC for geochronology. No previous age constraints are available for the RLIC as far as the author is aware. The RLIC is a prolific host to Proterozoic amethyst mineralization (Photo 9.1F) and multiple minor amethyst occurrences were noted within it during the field season. Locally, these amethyst veins also contain base metal sulphide mineralization (mainly galena, sphalerite and pyrite based on field observations).

Peraluminous Granites and Granitic Pegmatite Units

Neoarchean peraluminous granite intrusions and peraluminous granitic pegmatites are abundant in the map area. Field work in 2022 better characterized the peraluminous Hilma Lake granite and Voutilainen intrusion and granitic pegmatites in their vicinity.

HILMA LAKE GRANITE

The Hilma Lake granite underlies much of the southeastern part of the map area (*see* Figure 9.1). The northern part of the HLG is defined by the poorly exposed, geophysically and topographically interpreted Kingfisher fault (*see* Figure 9.1; Metsaranta 2015). The eastern contact of the HLG is outside of the map area. To the west and south, the HLG intruded clastic metasedimentary rocks. The bulk of the HLG comprises white to pink, medium-grained, massive to weakly foliated biotite-granite. Locally, biotite-muscovite– and muscovite-garnet– or biotite-muscovite-garnet–bearing assemblages are present suggesting strongly peraluminous compositions locally (Photos 9.2A and 9.2B). Along the northern margin of the HLG, several occurrences of peraluminous granitic pegmatites were observed to occur both within the HLG and as discrete intrusions into metasedimentary country rocks. These pegmatite bodies are texturally and compositionally heterogenous with coarsely crystalline zones that are quartz-alkali feldspar and plagioclase bearing with varying proportions of muscovite, biotite and garnet, and finer grained aplitic zones are commonly muscovite and garnet bearing. Locally, plumose graphic quartz-muscovite intergrowths are common (Photo 9.2C). Black tourmaline was also noted locally.

Limited mapping southwest of the HLG revealed the presence of thin coarse-grained peraluminous granitic dikes intruding clastic metasedimentary rocks locally, but no sampling was carried out. Thus, very little information is available for the rare-element potential southwest of the HLG. Additional work in this area is planned as a new north-south hydro powerline now provides access to the area.

VOUTILAINEN INTRUSION AND THE ONION LAKE PEGMATITES

Metsaranta and Walker (2019) mapped a more-or-less continuous, generally east-northeast-striking medium- to coarse-grained peraluminous granite (to the north) across the central portion of the map area. These granitic rocks are termed the Voutilainen intrusion (VI) for descriptive purposes (*see* Figure 9.1). The northern boundaries of the VI are more difficult to map because of shearing related to the Quetico deformation zone, which obscures original intrusive relationships to some degree, particularly in the eastern parts of the map area. Locally, both the southern and northern intrusive contacts of the VI are mappable. Granitic pegmatites in this general area were termed the Onion Lake pegmatites (OLP) by Breaks, Selway and Tindle (2003).

The bulk of the VI consists of medium-grained, variably foliated, white to light pink coloured, low magnetic susceptibility ($<0.1 \times 10^{-3}$ SI units) biotite and muscovite-biotite granite to granodiorite (Photo 9.2D). Commonly, the intrusion is also garnet bearing. Local variations in deformation state, textures and proportions of muscovite-biotite-garnet suggest that the VI could represent multiple different granite bodies. However, at the scale of mapping, subdivision into discrete intrusions has not been possible. More detailed analysis of geochemical data may reveal compositional differences in the future. The southern and northern margins of the VI contain zones of pegmatitic biotite-muscovite-garnet granite (Photo 9.2E). Pegmatitic intrusions (i.e., the Onion Lake pegmatites), likely derived from the VI, are present in clastic metasedimentary country rocks on both the north and south side of the VI (e.g., Photo 9.2F). Within these pegmatites, Breaks, Selway and Tindle (2003) noted an occurrence of beryl (UTM 346199E 5397916N, Zone 16), and an occurrence of ferrocolumbite (UTM 346512E 5398007N, Zone 16) immediately south of the VI along Highway 527 indicating that pegmatites of the beryl–niobium-tantalum oxide subtype (Černý 1991) occur in the western part of the map area.

Although no beryl or niobium-tantalum oxides were noted in the field, some additional pegmatites in the map area are likely of the beryl–niobium-tantalum oxide subtype (Černý 1991) based on preliminary whole-rock geochemical data generated by new mapping, sampling and whole-rock analysis. Six whole-rock samples of granitic pegmatites have beryllium contents above 98 ppm Be with a maximum value



Photo 9.2. Representative photos of peraluminous granites and granitic pegmatites in the map area. Photo locations are given as UTM co-ordinates using NAD83 in Zone 16. **A**) Blocky garnet- and muscovite-bearing potassium feldspar–rich pegmatite zone within medium-grained muscovite-garnet granite, Hilma Lake granite; compass for scale is 22 cm in length (UTM 367079E 5394911N). **B**) Red garnet crystals (~0.5 cm diameter) in granitic pegmatite in the central portion of the Hilma Lake granite; sighting arm of the compass used for scale is 7 cm long (UTM 367079E 5394911N). **C**) Plumose muscovite-quartz intergrowths in granitic pegmatite north of the Hilma Lake granite; compass for scale is 22 cm in length (UTM 362424E 5396080N). **D**) Typical exposure of the Voutilainen intrusion consisting of moderately fractured medium-grained muscovite-biotite granite; compass for scale is 22 cm in length (UTM 350311E 5399879N). **E**) Stripped exposure of garnet-biotite-muscovite–bearing granitic pegmatite and medium-grained garnet-biotite-muscovite granite organized into layer-like features near the southern margin of the Voutilainen intrusion; compass for scale is 22 cm in length (UTM 346817E 5398027N). **F**) Garnet replaced by black chlorite in a granitic pegmatite that intruded metawacke near the Voutilainen intrusion; sighting arm of the compass used for scale is 7 cm long (UTM 350734E 5400888N).

above the detection limit of 360 ppm Be. These samples also contain anomalous tantalum and niobium contents of between 63 and 173 ppm Ta and between 52 and 100 ppm Nb. These samples are sporadically distributed over 20 km along strike from Highway 527 to the eastern border of the map area.

WALKINSHAW LAKE PEGMATITES

Numerous pegmatite intrusions ranging from centimetre- to several metres-scale width form subconcordant, northeast striking and variably dipping, lensoid to dike-like bodies in metawacke along Highway 527 in the vicinity of Walkinshaw Lake (*see* Figure 9.1). Pegmatites in this area are typically quartz, alkali feldspar, green and silver muscovite dominated but were also observed to contain local black tourmaline and locally disseminated molybdenite mineralization. Breaks, Selway and Tindle (2003) sampled these granitic pegmatite dikes and found them to locally contain manganese-rich garnets (>30% spessartine component), fractionated whole-rock Mg/Li and Nb/Ta values and bulk feldspar with greater than 1000 ppm Rb indicative of crystallization from highly fractionated melts.

No obvious parent granite to these pegmatite intrusions has been mapped on surface. The Walkinshaw Lake pegmatites occur approximately 10 km south of the southern contact of the Voutilainen intrusion and separated from it by the Kingfisher fault and the predominantly metaluminous Whitelily Lake intrusion (*see* Figure 9.1). The spatial separation of Onion Lake pegmatites and the Walkinshaw Lake pegmatites suggests that they may be unrelated and that there may be multiple potentially rare-element fertile parent granite–pegmatite systems in the area.

Metavolcanic Rocks

In the southeastern portion of the map area, east of the Hilma Lake granite, an approximately 1 km wide band of mafic metavolcanic rocks locally interlayered with sulphidic argillite and fine-grained melagabbroic sills was discovered after investigating a high magnetic anomaly (*see* "2022 Field Season Highlights"). Preliminary field work showed that this mafic metavolcanic unit is intercalated with clastic metasedimentary rocks with bedding that is west striking and dips steeply to the north but youngs toward the south. Locally, pillowed mafic flows with pillow shelves also young toward the south and dip to the north. Strain is greater on the northern margin of the mafic metavolcanic unit and locally stretching lineations defined by elongated pillows plunges steeply toward the north. However, neither contact (i.e., upper and lower) of this mafic metavolcanic unit with the clastic metasedimentary rocks was directly observed on the field. Similar rocks occur along the northeastern margin of the Roll Lake intrusive complex (*see* Figure 9.1) and as discontinuous outcrops within it and also to the west of the Roll Lake intrusive complex as a southwest-striking mafic metavolcanic–dominated unit that extends from Kingfisher Lake to the Hazelwood Lake area just west of the map area.

An occurrence of felsic metavolcanic rocks was noted in the southern part of the map area along the northern margin of the Mount Baldy intrusion. Previous mapping by Scott (1990) showed only mafic metavolcanic rocks in this area. Felsic metavolcanic rocks at this outcrop include fine-grained autobrecciated flows, tuff and tuff breccia.

EXPLORATION RECOMMENDATIONS

Continuing advanced exploration of the Thunder Bay North intrusive complex is being carried out for nickel-copper-platinum group element mineralization in the northern part of the map area and remains the most promising exploration target (e.g., Campbell et al. 2022). However, the area also has potential for several other commodities, some of which are highlighted in the following section. Additional discussions on mineral potential of the area are provided in Metsaranta (2015) and Metsaranta and Walker (2019).

Peraluminous Granitic Pegmatite Related Rare-Element–Molybdenum Mineralization

As noted by Breaks, Selway and Tindle (2003) and supported by the results of new mapping, rare-element pegmatites, of the beryl–niobium-tantalum oxide subtype (Černý 1991) occur in the project area. However, to date, no pegmatites of more evolved lithium-rich pegmatite types have been identified. Additional mapping and preliminary geochemical data produced during this project have extended the known zone of rare-element (Be-Nb-Ta) mineralized pegmatites and potential parent granites from Highway 527 to the eastern edge of the map area. The southern and northern margins of the Voutilainen intrusion and pegmatites in this area should be prospected for rare-element mineralization.

To the west, outside of the map area, only reconnaissance mapping has so far been carried out. However, medium-grained peraluminous granites and local granitic pegmatites also occur in this area. The Buda pegmatite (Breaks, Selway and Tindle 2003; *see also* OMI record MDI52A12NW00003, Ontario Geological Survey 2022), which occurs in Goldie Township, approximately 55 km to the west of the Onion Lake pegmatites and in a similar geological setting, contains manganese-rich garnet and minor niobium-oxides (Breaks, Selway and Tindle 2003). Thus, niobium-tantalum oxide and/or beryllium-bearing granitic pegmatites occur discontinuously along a strike length of at least 75 km in the southern part of the project area.

Polymetallic Silver-Gold-Bismuth-Lead-Copper-Zinc-Barite-Amethyst Veins

The Ontario Mineral Inventory includes many occurrences of amethyst in the map area and several of these have been or are being quarried for amethyst. During the summer, minor amethyst veins were noted at several places and several of these quartz-carbonate vein systems locally host barite, galena, sphalerite and/or pyrite. Campbell et al. (2022) reported sampling of veins in the Magone Road area on claims held by P. Gehrels. Some samples contained appreciable silver, gold, bismuth and lead contents. Campbell et al. (2022) reported that “Sample 21DCPG006, located at 352513E 5385243N, returned greater than 80 ppm Ag, 3688 ppm Cu and greater than 1200 ppm Bi”. These results suggest that Proterozoic vein systems, a considerable distance “inboard” from rocks of the Midcontinent Rift, may have silver mineralization potential comparable to the Mainland and Island silver belts located farther to the southeast (e.g., Franklin et al. 1986). Samples of this style of mineralization, collected during the summer of 2022, will be submitted for analysis.

FUTURE WORK

Mapping at 1:50 000 scale of the larger project area will likely continue for at least 2 more field seasons. During 2023, the focus of mapping will shift to the west to cover those portions of the project area represented by National Topographic System 1:50 000 scale maps 52 A/11 (including Fowler, Jacques, Ware and Gorham townships) and 52 A/12 (Soper, GTP Block 1, Goldie and Forbes townships) that comprise the southern portion of project area (*see* Metsaranta and Walker 2019).

ACKNOWLEDGMENTS

We would like to thank Fort William First Nation, Lac La Croix First Nation, Red Rock Indian Band, Métis Nation of Ontario Region 2 Thunder Bay Métis Council and Red Sky Métis Independent Nation for allowing the Ontario Geological Survey to map in their traditional land use area. Their co-operation is greatly appreciated.

Tara Doherty and Colleen Kurcinka (Thunder Bay Resident Geologist's Office) provided exemplary assistance with field work during 2022 field season. Manuel Duguet, Dorothy Campbell, Mark Puumala and Rob Cundari are thanked for numerous discussions about the geology of the field area over the years. Joe Walker mapped much of the area during 2019.

Thank you to Geoff Heggie and Al MacTavish (Clean Air Metals Ltd.) for allowing and facilitating access to core and proprietary data sets and for discussions about the geology of area.

Manuel Duguet (Earth Resources and Geoscience Mapping Section, OGS) and Monica Gaiswinkler Easton (Publication Services, OGS) are thanked for their reviews and improvements to the article. Thanks to Pat Gervais also for drafting.

REFERENCES

Breaks, F.W., Selway, J.B. and Tindle, A.G. 2003. Fertile peraluminous granites and related rare-element mineralization in pegmatites, Superior Province, northwest and northeast Ontario: Operation Treasure Hunt; Ontario Geological Survey, Open File Report 6099, 179p.

Campbell, D.A., Jonsson, J.R.B., Kurcinka, C.E., Dorland, G., Pettigrew, T.K., Daniels, C.M. and Bousquet, P. 2022. Report of Activities 2021, Resident Geologist Program, Thunder Bay South Regional Resident Geologist Report: Thunder Bay South District; Ontario Geological Survey, Open File Report 6383, 102p.

Černý, P. 1991. Rare-element granitic pegmatites, part I. Anatomy and internal evolution of pegmatite deposits; Geoscience Canada, v.18, p.49-67.

Franklin, J.M., Kissin, S.A., Smyk, M.C. and Scott, S.D. 1986. Silver deposits associated with the Proterozoic rocks of the Thunder Bay District, Ontario; Canadian Journal of Earth Sciences, v.23, p.1576-1591.

Lassen, B. 2004. Petrogenesis of the Late Archean Quetico alkaline suite intrusions, western Superior Province, Canada; unpublished PhD thesis, University of Ottawa, Ottawa, Ontario, 250p.

Metsaranta, R.T. 2015. Preliminary results from geological mapping of the Quetico Subprovince, the Shebandowan greenstone belt and Proterozoic rocks north of Thunder Bay; *in* Summary of Field Work and Other Activities, 2015, Ontario Geological Survey, Open File Report 6313, p.15-1 to 15-20.

Metsaranta, R.T. and Hamilton, M.A. 2020. A precise U/Pb age for a north-trending mafic dike from the western flank of the Marathon Swarm, East Bay area, northwestern Ontario; *in* Summary of Field Work and Other Activities, 2020, Ontario Geological Survey, Open File Report 6370, p.7-1 to 7-9.

Metsaranta, R.T. and Kamo, S.L. 2021. A uranium–lead baddeleyite age for the Midcontinent Rift–related Lone Island Lake intrusion, northwestern Ontario; *in* Summary of Field Work and Other Activities, 2021, Ontario Geological Survey, Open Filed Report 6380, p.12-1 to 12-8.

Metsaranta, R.T. and Walker, J.A. 2019. Precambrian geology of western McGregor Township and adjacent areas, northeast of Thunder Bay; *in* Summary of Field Work and Other Activities, 2019, Ontario Geological Survey, Open File Report 6360, p.11-1 to 11-10.

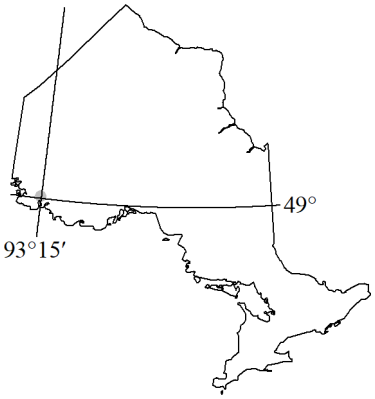
Ontario Geological Survey 2019a. Mineral Deposit Inventory; Ontario Geological Survey, Mineral Deposit Inventory (September 2019 update), online database.

——— 2019b. Ontario Drill Hole Database; Ontario Geological Survey, Ontario Drill Hole Database (2019 update), online database.

——— 2022. Ontario Mineral Inventory; Ontario Geological Survey, Ontario Mineral Inventory (September 2022 update), online database.

Scott, J. 1990. Geology of MacGregor Township; Ontario Geological Survey, Open File Report 5719, 82p.

10. Project NW-22-001. Precambrian Geology of the Straw Lake–Esox Lake Area, Western Wabigoon Subprovince, Northwestern Ontario



S.R. Meade[1]

[1]Earth Resources and Geoscience Mapping Section, Ontario Geological Survey

INTRODUCTION

The Straw Lake–Esox Lake area is located approximately 60 km north of Fort Frances and 80 km south of Dryden and is part of the Archean Wabigoon Subprovince. For this study, the area was accessed via Cedar Narrows Road off Highway 502. The area is underlain by an east-trending belt of metavolcanic and metasedimentary rocks that are intruded by a series of granitic plutons. The supracrustal rocks are cut by the east-trending Manitou Straits–Pipestone fault zone, a crustal-scale shear zone that is regionally interpreted to be part of the Pipestone–Cameron fault zone, exposed just west of the study area (Edwards 1983). Numerous gold occurrences are noted along the trace of the fault zone, particularly in the area around Straw Lake where the Straw Lake Beach Mine operated in the 1930s (Figure 10.1).

The study area was mapped in detail most recently by Edwards (1983) and Smith (1993). These studies were conducted shortly after the area had been logged, taking advantage of bedrock exposures along active forest access roads. These previous studies produced excellent lithological mapping and comprehensive reports on the area's geology. Geological mapping was undertaken in the Straw Lake–Esox Lake area in 2022 as the continuation of a multi-year mapping study of the Rowan–Kakagi greenstone belt (Meade 2015). The objective of the regional study has been to characterize the major shear zones, their associated hydrothermal alteration and gold occurrences. In addition, samples for geochemistry and geochronology have been collected to identify and classify late-tectonic granites throughout the greenstone belt because of their importance in gold mineralizing systems (Beakhouse 2007).

The Straw Lake–Esox Lake area is of particular interest because of the occurrence of coarse clastic sedimentary rocks around Esox Lake. The spatial association between gold mineralization and syntectonic sedimentary rocks has long been recognized in major gold camps in Ontario, most notably the Timiskaming conglomerates that occur in the Abitibi region (Ayer et al. 2005). No metasedimentary rocks are preserved around the gold deposits in the Cameron Lake area to the west of Straw Lake. However, characterizing the metasedimentary rocks in the Straw Lake–Esox Lake area and determining their relationship to regional deformation and gold mineralization may provide some insights on whether or not the model established for gold mineralization in the Abitibi region is applicable to the Straw Lake–Esox Lake area.

GEOLOGICAL SETTING

The metavolcanic and metasedimentary succession in the study area is bounded to the north and south by large intrusive complexes, composed of diorite, syenodiorite and granodiorite, named the Lawrence Lake batholith and the Jackfish Lake complex, respectively (*see* Figure 10.1).

Summary of Field Work and Other Activities, 2022,
Ontario Geological Survey, Open File Report 6390, p.10-1 to 10-6.

© King's Printer for Ontario, 2022

The greenstone belt is transected by the Manitou Straits–Pipestone fault zone. In the study area, the fault is characterized by the development of a zone of strong planar fabric with intense iron carbonate and sericite alteration. Unfortunately, the rocks within the deformation zone rarely show definitive kinematic indicators because of the intensity of alteration. Further studies will be necessary to decipher the strain regime of the Manitou Straits–Pipestone fault zone.

North of the Manitou Straits–Pipestone fault zone, the metavolcanic assemblage is dominated by intermediate to felsic volcanic rocks including light green weathering, lapilli tuff and tuff breccia. Minor mafic pillowed lava flows occur in the succession and are typically plagioclase phyric. Voluminous feldspar porphyritic rocks occur throughout the succession and are interpreted to be synvolcanic sills. The sills are typically strongly foliated and locally altered by iron carbonate and sericite.

South of the Manitou Straits–Pipestone fault zone, the rocks are predominantly mafic volcanic flows, mostly massive, locally with plagioclase phenocrysts; pillowed lava flows occur rarely in the study area. The southern half of Esox Lake is underlain by a feldspar to quartz-feldspar porphyry, interpreted to be a subvolcanic intrusion. The northern part of the lake exposes the metasedimentary unit that is composed of medium- to fine-grained sandstones and silty mudstones. Some portions of the unit are massive with no defined bedding, but much of the succession, particularly in the northern part of Esox Lake, is medium-bedded sandstone with thin interlayers of parallel laminated mudstone. Beds of feldspar crystal tuff also occur locally within the metasedimentary unit. The central part of Esox Lake is underlain by granite of the

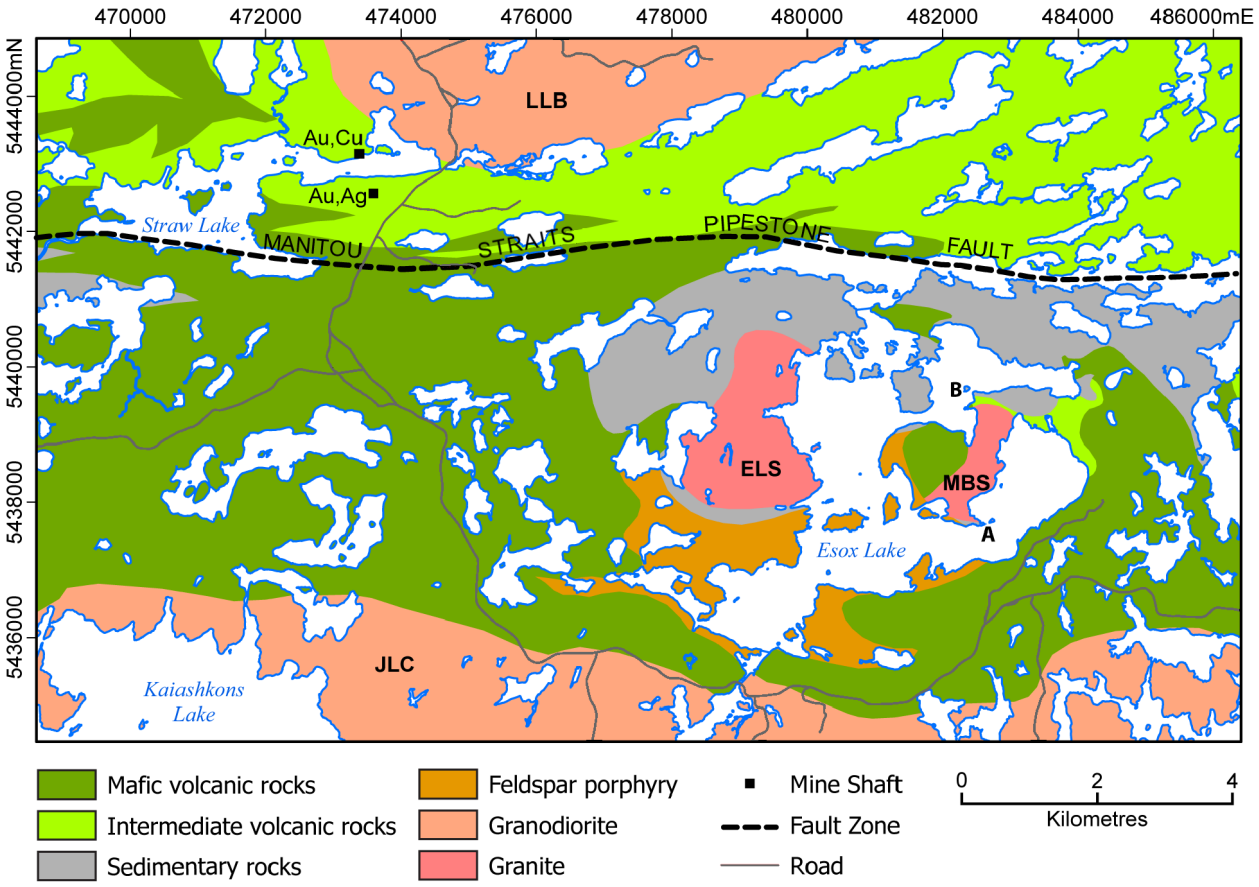


Figure 10.1. Simplified geological map of the Straw Lake–Esox Lake area. Letters "A" and "B" label locations referred to in the text. Abbreviations for intrusions named in the text: LLB, Lawrence Lake batholith; ELS, Esox Lake stock; MBS, Mirror Bay stock; JLC, Jackfish Lake complex. Universal Transverse Mercator (UTM) co-ordinates provided using North American Datum 1983 (NAD83) in Zone 15.

Esox Lake stock and the Mirror Bay stock (*see* Figure 10.1). Both granites are medium grained, equigranular and massive.

Gold occurrences in the Straw Lake–Esox Lake area are typical of shear zone–hosted gold deposits throughout the Wabigoon Subprovince. Gold is hosted by highly sheared quartz-carbonate altered intermediate to felsic metavolcanic rocks with pyrite and chalcopyrite.

METASEDIMENTARY ROCKS

The feldspar porphyry exposed in the southern part of Esox Lake has an unusual texture described by Edwards (1983) as "autoclastic" referring to the local occurrence of what appears to be areas of annealed breccia (Photo 10.1A). Edwards (1983) suggests that the texture may be related to the unroofing of the intrusion. The occurrence of "autoclastic" texture is more prevalent in the northern part of the unit suggesting that the intrusion is tilted along with the rest of the stratigraphy and the upper part of the intrusion is exposed toward the north. This is consistent with observations of the basal unconformity of the metasedimentary unit, which is exposed in a narrow belt of outcrop on the shoreline of Mirror Bay in Esox Lake (*see* Figure 10.1, location A). At this locality, the porphyry shows an irregularly shaped surface interpreted to be an erosional contact. The paleotopography lows or troughs in the surface are filled mostly by clays and fine-grained sediment. At 1 locality, beds of chert onlap the edge of the unconformity surface. The chert beds dip steeply toward the south indicating that the beds and the erosional surface of the porphyry are overturned (*see* Photo 10.1B). Immediately north of the unconformity surface are outcrops of a poorly sorted, pebble to cobble, clast-supported conglomerate composed of angular to subrounded clasts of quartz-feldspar porphyry and fine-grained mafic volcanic rock (*see* Photo 10.1C). The clasts are cemented together by a fine-grained calcareous matrix.

The unconformity between the feldspar porphyry and the conglomerate appears prominently from the shoreline of Mirror Bay because of its pronounced gossanous weathered surface. The unconformity is hydrothermally altered and contains clots of semi-massive, fine-grained pyrite. The overlying conglomerate locally contains stringers of coarse-grained, subhedral pyrite.

The conglomerate at Mirror Bay is overlain by bedded sandstone with planar layers of silty mudstone (*see* Photo 10.1D), which is the most common metasedimentary rock in the map area. The exposure (*see* Figure 10.1, location A) suggest that the conglomerate unit is less than 10 m in thickness.

The bedded sandstones do not show evidence of grading, cross lamination or scour-based beds, rather they appear to represent the distal portion of a turbidite succession in a low-energy, deep marine environment. The juxtaposition of the poorly sorted angular conglomerate and the rhythmically layered fine-grained sandstones, as well as the underlying chert beds, has been attributed to 2 possible mechanisms. The occurrence of quartz-feldspar porphyritic clasts in the conglomerate led Edwards (1983) to suggest that the conglomerate is derived locally as a unit formed during the unroofing of the underlying feldspar porphyry intrusion. Conversely, the conglomerate is characterized as a debris flow by Smith (1993), who suggests that the detritus is sourced from a structural culmination to the north that formed over the Manitou Straits–Pipestone fault zone.

The basal conglomerate of the metasedimentary unit is exposed at 1 other locality on a small island in Canoe Bay on Esox Lake (*see* Figure 10.1, location B). This outcrop lies north of the Mirror Bay stock, indicating that the unconformity is warped around the younger granitic intrusion. At this locality, the conglomerate outcrop is restricted entirely to the island, so the stratigraphic relationship between the conglomerate and the metasedimentary rocks to the north and the metavolcanic rocks to the south are not exposed. The exposure in Canoe Bay does, however, indicate that the conglomerate is at least 75 m thick, showing that the unit thickens toward the north. This observation supports the theory that the conglomerate

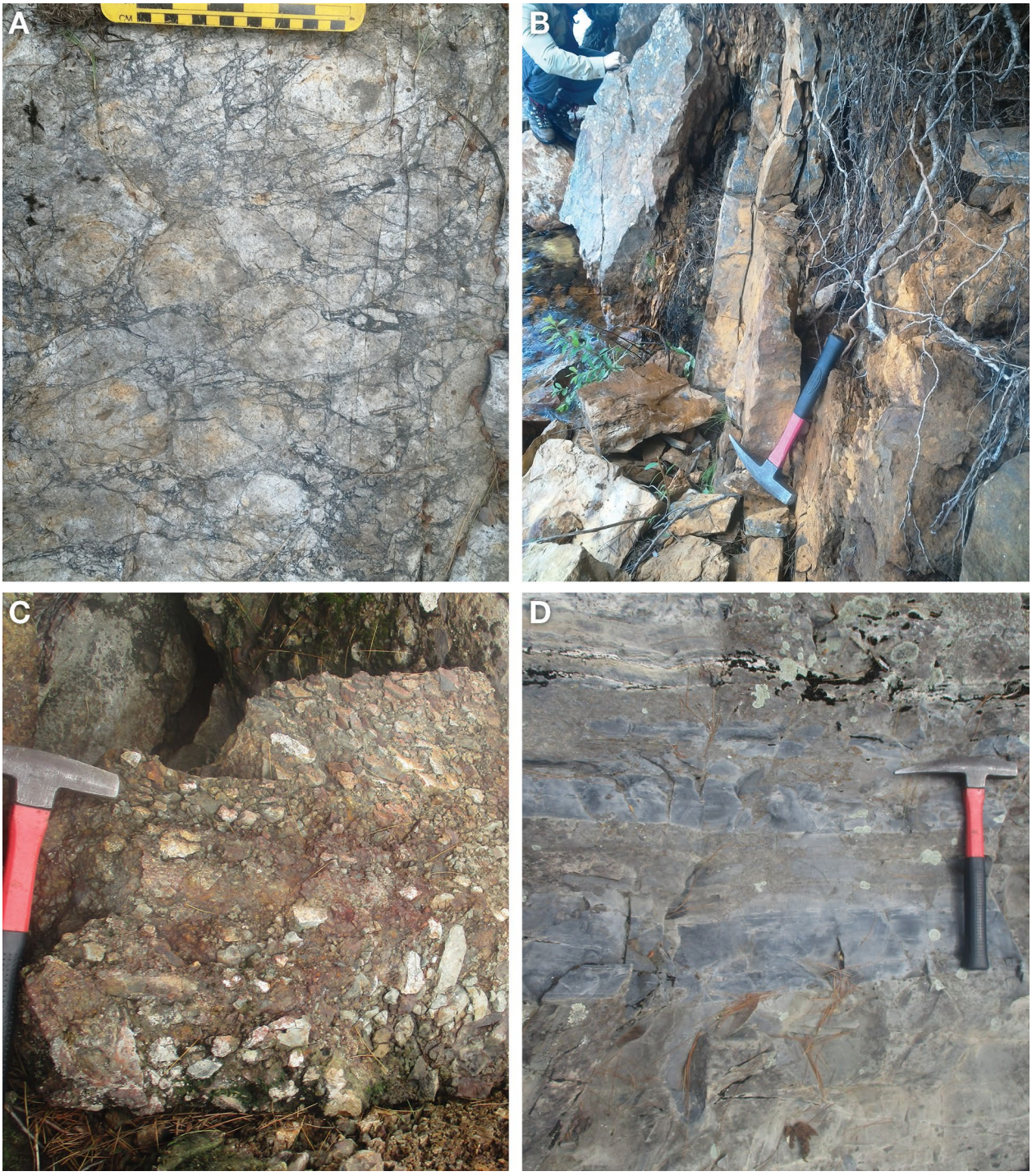


Photo 10.1. A) "Autoclastic" texture in feldspar porphyry (UTM 481057E 5438543N). **B)** Unconformity between feldspar porphyry and metasedimentary unit. The feldspar porphyry is exposed in the left side of the photo: its irregular surface is filled with fine-grained sediment that is overlain by brown-weathering chert beds in the centre of the photo. The beds dip steeply toward the south indicating that the unconformity is overturned (UTM 482626E 5437660N). **C)** Poorly sorted, clast-supported conglomerate with white-weathering subangular clasts of feldspar porphyry (UTM 482626E 5437660N). **D)** Bedded sandstone with parallel laminated layers of mudstone (UTM 482626E 5437665N). All UTM co-ordinates provided using NAD83 in Zone 15. Hammer for scale is 35 cm long.

is a debris flow or alluvial fan deposit sourced from a topographic high in the northern part of the greenstone belt. A detailed petrographic analysis of the conglomerate clasts and the sandstone will be carried out to determine the provenance of the metasedimentary units.

CONCLUSIONS

Coarse clastic sedimentary rocks in the Esox Lake area are polymictic with angular, poorly sorted clasts, much like the syntectonic sedimentary units typical of fault zones. Based on current mapping, further petrographic study is required to make a clear correlation between deformation on the Manitou Straits–Pipestone fault zone and deposition of sedimentary rock units at Esox Lake. More work is also warranted to evaluate the nature of the metasedimentary successions in the Pipestone Lake area to the west and along the shores of Upper Manitou and Lower Manitou lakes to the east.

The lack of younging indicators in the metasedimentary and metavolcanic successions and the lack of meso-scale fold structures makes it difficult to estimate the true thickness of supracrustal units or make inferences on whether the succession has been structurally repeated. Geological contacts, including the unconformity at the base of the metasedimentary unit, are highly modified by emplacement of granite intrusions (e.g., Esox Lake stock and Mirror Bay stock) at Esox Lake. During this study, the Esox Lake stock and the upper portion of the metasedimentary unit were sampled for geochronological analysis to determine the age range of the late stage of the tectonic evolution of the greenstone belt.

Despite the ambiguity surrounding the provenance of potential syntectonic sedimentary rocks, the Straw Lake–Esox Lake area has potential for new discoveries of shear zone–hosted gold mineralization along the trace of the Manitou Straits–Pipestone fault zone. It is also compelling that the basal unconformity of the metasedimentary unit is the site of secondary sulphide mineralization. This may indicate that these rocks have potential to host volcanogenic massive sulphide–style mineralization similar to the synvolcanic gold-copper deposits at the nearby Mayburn Mine (Link 2008).

ACKNOWLEDGMENTS

The author wishes to thank E. Cohen for his assistance in the field as well as E.G. Amyotte, Resident Geologist, Kenora, for his contribution to this project. Field work was supported by Science Leaders and Geoscience Applicationists at the Ontario Geological Survey. The author would like to thank Couchiching First Nation, Mitaanjigamiing First Nation, Métis Nation of Ontario Sunset Country, Naicatchewenin First Nation and Rainy River First Nation for allowing the Ontario Geological Survey to map their traditional land use area.

REFERENCES

Ayer, J.A., Thurston, P.C., Bateman, R.J., Dubé, B., Gibson, H.L., Hamilton, M.A., Hathway, B., Hocker, S.M., Houlé, M.G., Hudak, G., Ispolatov, V.O., Lafrance, B., Lesher, C.M., MacDonald, P.J., Péloquin, A.S., Piercey, S.J., Reed, L.E. and Thompson, P.H. 2005. Overview of results from the greenstone architecture project: Discover Abitibi Initiative; Ontario Geological Survey, Open File Report 6154, 146p.

Beakhouse, G.P. 2007. Structurally controlled, magmatic hydrothermal model for Archean lode gold deposits: A working hypothesis; Ontario Geological Survey, Open File Report 6193, 133p.

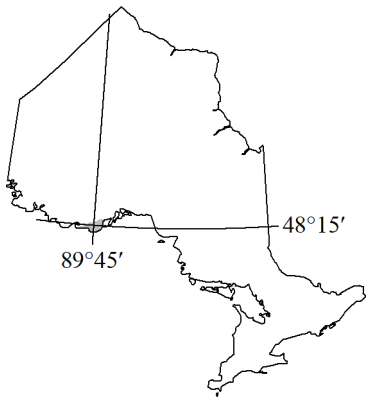
Edwards, G.R. 1983. Geology of the Straw Lake area, districts of Kenora and Rainy River; Ontario Geological Survey, Report 222, 67p.

Link, T.A. 2008. Report on diamond drilling AT-08-001 to 009 Atikwa Lake property, Atikwa Lake Twp., Ontario, prepared for Opawica Explorations Inc.; report, Kenora Resident Geologist's office, assessment file AFRI# 20000003515, 164p.

Meade, S.R. 2015. A new mapping project in the Rowan Lake–Kakagi Lake area, western Wabigoon Subprovince; *in* Summary of Field Work and Other Activities, 2015, Ontario Geological Survey, Open File Report 6313, p.12-1 to 12-6.

Smith, P.M. 1993. Precambrian geology, Vista Lake area; Ontario Geological Survey, Report 282, 84p.

11. Project NW-22-002. Reconnaissance Bedrock Geology Mapping of the Animikie Basin and Spatially Associated Midcontinent Rift–Related Igneous Rocks, Thunder Bay Area, Northwestern Ontario: A Project Introduction



R.T. Metsaranta[1] and C.E. Kurcinka[2]

[1]Earth Resources and Geoscience Mapping Section, Ontario Geological Survey, Sudbury, Ontario P3E 6B5
[2]Resident Geologist Program, Thunder Bay South District, Ontario Geological Survey, Thunder Bay, Ontario P7E 6S7

INTRODUCTION

During the summer of 2022, the Earth Resources and Geoscience Mapping Section (ERGMS) and the Resident Geologist Program (RGP) Thunder Bay South District began a collaborative project to produce new 1:50 000 scale bedrock geology maps of the Animikie Group and spatially associated igneous rocks related to the Midcontinent Rift in the area between the city of Thunder Bay and the border with the United States of America (USA) (Figure 11.1). The project was motivated by a lack of mapping and the aging vintage of existing mapping of the area and by revived interest in the nickel-copper-platinum group elements (PGE) potential of intrusive rocks related to the Midcontinent Rift (e.g., Smith et al. 2019; Bleeker et al. 2020). The project aims to produce up-to-date maps through comprehensive data compilation, targeted field work (focus on areas of no previous mapping) and geophysical interpretation.

The Animikie Group and related rocks are exposed in Ontario, Minnesota, Wisconsin and Michigan and formed in an active tectonic setting during the Paleoproterozoic (~1.9 to 1.8 Ga) along the southern margin of the Superior Province (i.e., "The Penokean Orogeny"; Ojakangas, Morey and Southwick 2001; Schultz and Cannon 2007). Sedimentary and volcanic rocks deposited in the Animikie Basin occur along the northwest and south shores of Lake Superior and represent a unit of globally significant mineral wealth in the form of iron deposits (the USA portion of the Animikie Basin) that have been mined since the late 19th century (e.g., Morey 1983; Konhauser et al. 2017). Significant base metal resources (volcanogenic massive sulphide type) are also present in the Penokean volcanic belt of Wisconsin and Michigan (e.g., Dematties 2022), which contains arc-related volcanic rocks that are of the same age as Animikie Group rocks in Ontario (e.g., Fralick, Davis and Kissin 2002; Zi et al. 2022). The Animikie Group also has significant global scientific importance as it contains well-preserved microfossil assemblages and chemical sedimentary rocks that provide a record of Earth's evolving biology and geochemical systems during the Paleoproterozoic (e.g., Javaux and Lepot 2018; Poulton, Fralick and Canfield 2004).

Summary of Field Work and Other Activities, 2022,
Ontario Geological Survey, Open File Report 6390, p.11-1 to 11-13.

© King's Printer for Ontario, 2022

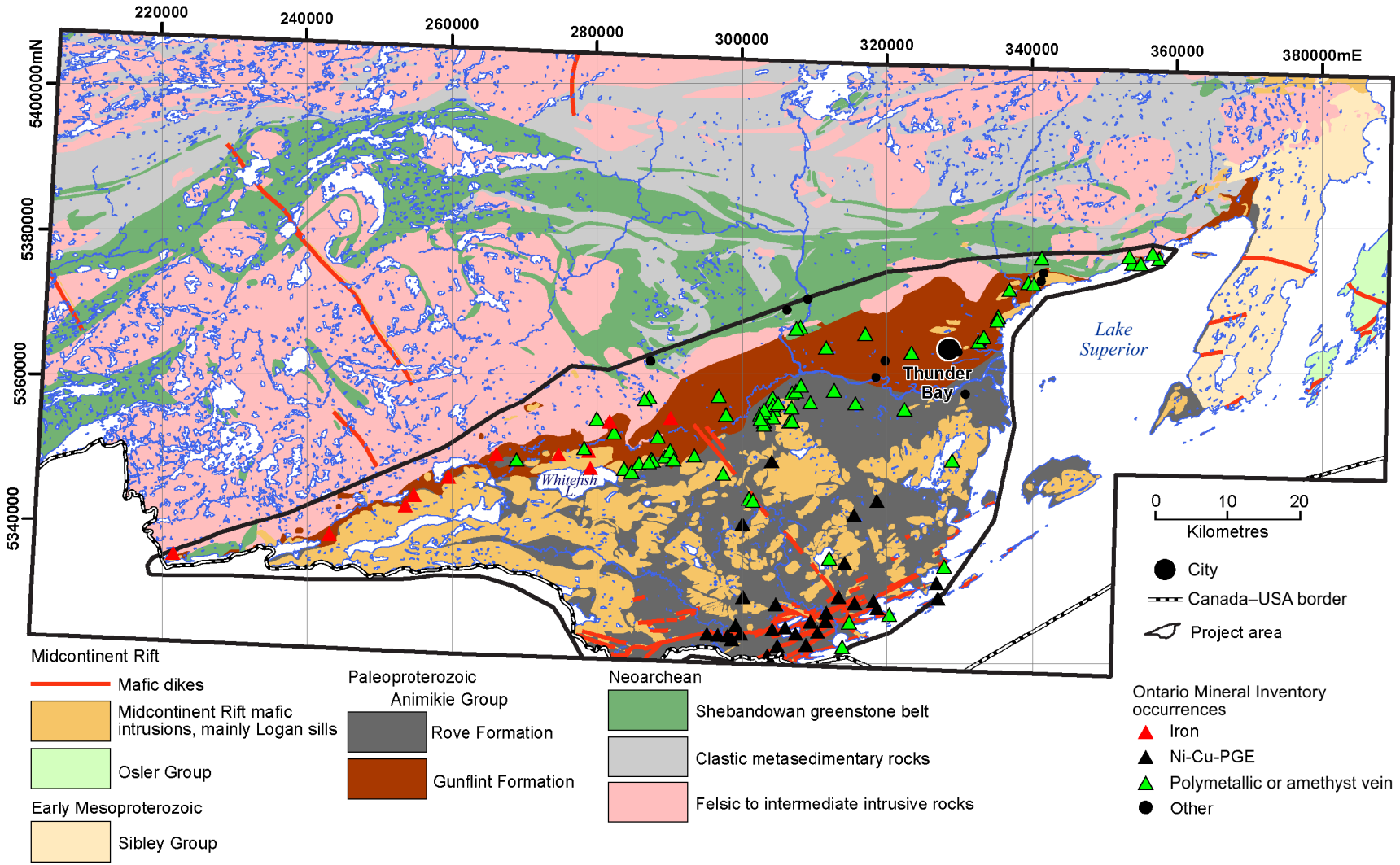


Figure 11.1. Location of the project area and regional geology *modified from* Santaguida (2001a, 2001b) and Ontario Geological Survey (2011), mineral occurrence types shown are simplified *from* the Ontario Mineral Inventory (Ontario Geological Survey 2022).

Midcontinent Rift–related intrusions emplaced into Animikie Group and other rocks of the same age host significant nickel-copper-PGE deposits in the USA (Duluth Complex, Eagle and Tamarack deposits, *see* reviews by Smith et al. (2019) and Bleeker et al. (2020)) and minor deposits and occurrences in Canada (e.g., Great Lakes Nickel deposit: MDI52A04SE00026, Ontario Geological Survey 2022). Animikie Group rocks in the project area also contain several polymetallic vein deposits of Keweenawan age that produced silver during the late 19th century (Franklin et al. 1986).

This article is intended to provide a broad introduction to the geology of the project area and provides a general synopsis of previous mapping of the area by the Ontario Geological Survey (OGS) and Geological Survey of Canada (GSC), a summary of the regional geology based on previous work, a description of preliminary field work carried out during the summer of 2022 and a brief review of the mineral occurrence types in the area.

PREVIOUS MAPPING BY THE ONTARIO GEOLOGICAL SURVEY AND THE GEOLOGICAL SURVEY OF CANADA

This section briefly reviews previous mapping of the project area by the OGS (or its predecessors) and the GSC. A review of the extensive body of scientific literature concerning the Animikie Group and Midcontinent Rift is not attempted.

Some portions of the project area were mapped and reported on by the GSC (*see* Gill 1925; Tanton 1931a, 1931b) and remain an invaluable source of information about the geology of the Animikie Group. These authors also provide a good bibliography of mid- to late-19th century and earlier 20th century geological studies in the area, the earliest of which includes work by Sir William Logan during the mid-19th century. Many early studies were focussed on the silver deposits of the region (Ingall 1888; Bowen 1911a, 1911b). Sketch maps in Gill (1925) serve as the only relatively detailed mapping of some parts of the southwestern portion of the project area.

Most of the eastern part of the map area, including the City of Thunder Bay, was mapped by the OGS; however, small-scale compilation maps provide the only available mapping in the southwestern part of the project area. In the early 1960s, 2 reports focussed on the Gunflint Formation and its iron potential (Goodwin 1960a; Moorhouse 1960a). As part of these studies, a series of 8 maps at 1 inch to ½ mile scale (i.e., 1:31 680) were published (Goodwin 1960b; Moorhouse 1960b, 1960c, 1960d, 1960e; Moorhouse and Goodwin 1960a, 1960b, 1960c). Mapping of Macgregor Township by Scott (1990) provides some relatively recent mapping of the Animikie Group northeast of the City of Thunder Bay.

Geul carried out mapping in the southeastern portions of the project area in the late 1960s (Geul 1969a, 1969b, 1970a, 1970b). This mapping at 1 inch to ½ mile scale (1:31 680) covered areas underlain mainly by the Rove Formation, the Logan sills, the Crystal Lake Gabbro and various Midcontinent Rift–related dikes. A broader map encompassing the earlier mapped areas by Geul was completed by Smith and Sutcliffe (1989) at the 1:50 000 scale. Sutcliffe (1991) includes a synopsis the Proterozoic geology of the Lake Superior area in Ontario.

Coloured compilation maps of the project area were completed by Santaguida (2001a, 2001b) at a scale of 1:250 000. Earlier compilation maps include 1:126 720 scale maps published by Pye and Fenwick (1963).

During 2015, the OGS flew new medium resolution geophysics over much of the area (Ontario Geological Survey 2015).

REGIONAL GEOLOGY AND PRELIMINARY FIELD OBSERVATIONS

This section provides a synopsis of the geology within the project area. The regional geology of the project area is outlined on Figure 11.1. The general descriptions from the literature of the stratigraphic units are supplemented by field observations made during the course of the summer 2022. Field work completed in 2022 was mainly a preliminary reconnaissance and more detailed investigations will take place in the next field seasons.

The Animikie Group

The Animikie Group ("Series" in older literature) in Ontario consists of 3 units: the Kakabeka conglomerate, the Gunflint Formation and the Rove Formation (e.g., Tanton 1931a; Goodwin 1956). Animikie Group rocks generally dip gently toward the southeast and, as such, the lowermost units are exposed on the northern rim of the basin and successively younger units are exposed to the south. Rare folds are present in Gunflint Formation rocks (e.g., Moorhouse 1960a), but Rove Formation rocks are typically not deformed. Faults related to the Midcontinent Rift locally offset all rock units in the area.

KAKABEKA CONGLOMERATE

The Kakabeka conglomerate is a thin, discontinuous, but widespread siliciclastic conglomerate that rests unconformably on Archean basement rocks (Photo 11.1A). According to Tanton (1931a), the Kakabeka conglomerate reaches a maximum thickness of 4 feet (~1 m). The Kakabeka conglomerate may be correlative with the thicker Pokegama Quartzite (Ojakangas, Morey and Southwick 2001) that forms the base of the Animikie Group in Minnesota, or it may be more reasonable to consider it as a lower member of the Gunflint Formation.

During the field season, a sample of the Kakabeka conglomerate from an exposure on Highway 11–17 south of Pass Lake (*see* Photo 11.1A) was collected for geochronology to characterize the provenance of the unit as well as to constrain a maximum depositional age for the lower Gunflint Formation. The conglomerate has a clast-supported texture, consists of coarse-grained sand, granules, pebbles and rare cobbles in a sandy matrix (Photo 11.1B). Quartz, pink granitoid, clastic metasedimentary and mafic metavolcanic clasts were observed in the conglomerate exposure. It occurs in discontinuous fashion in limited portions of the outcrop and is generally less than 50 cm thick.

GUNFLINT FORMATION

The Gunflint Formation is composed of a variety of chemical sedimentary rocks, clastic sedimentary rocks and minor volcanic rocks (e.g., Gill 1925). The Gunflint Formation crops out mainly in a belt from the Gunflint Lake area at the Minnesota–Ontario border to the Loon Lake area, and then discontinuously along the north shore of Lake Superior as far as the Slate Islands. The maximum thickness of the Gunflint Formation is estimated to be about 175 to 200 m and a generally accepted age of the Gunflint Formation is 1878±1.3 Ma (U/Pb, interpreted volcaniclastic zircon: Fralick, Davis and Kissin 2002). The top of the Gunflint Formation is marked by rocks containing intraformational breccias, accretionary lapilli, spherules and shocked quartz which are interpreted to represent ejecta from the Sudbury impact event that occurred at *circa* 1850 Ma (Addison et al. 2005; Krogh, Davis and Corfu 1984). Bedrock mapping, as summarized by Moorhouse (e.g., 1960a) and Goodwin (1960a), subdivided the Gunflint Formation into a lower (basal conglomerate, lower algal chert, lower shale, lower taconite) and upper (local lava flows, upper algal chert, upper jasper, upper shale, upper taconite and upper limestone) units, and a unit of "argillite-tuff" (essentially shale and local tuff that occurs in the middle part of the Gunflint Formation



Photo 11.1. Representative photos of the Gunflint Formation in or near the project area. Photo locations are given as Universal Transverse Mercator (UTM) co-ordinates in North American Datum 1983 (NAD83). **A)** Basal unconformity between the Animikie Group and the underlying chloritized Archean rocks. Person for scale is 170 cm tall (UTM 367861E 5383579N, Zone 16). **B)** Typical sample of the basal Kakabeka conglomerate that patchily overlies the Archean basement. The sample is taken from the same outcrop shown in Photo 11.1A. **C)** Mound-shaped stromatolites resting on chloritized Archean basement. Stromatolite contains a core of black chert, whereas the outer layer is composed of red chert. Typical Gunflint Formation grainstones are visible onlapping the stromatolite mound (UTM 367643E 5383270N, Zone 16). **D)** Pyrite nodules (some showing radial fabric) up to 5 cm wide in lower Gunflint Formation shale (UTM 686091E 5335562N, Zone 15). **E)** Pisolith-like nodules exhibiting a red hematite rim with a calcite core surrounding strongly magnetic granular iron formation (UTM 688968E 5335853N, Zone 15). **F)** Plan view photo of typical exposure of weathered unit mapped as "Gunflint Lavas" near Mink Mountain. Compass for scale is 7.1 cm wide (UTM 714524E 5348311N, Zone 15).

and mostly in the eastern part of the project area). In the project area, the stratigraphy of the Gunflint Formation is complex and characterized by rapid lateral changes in lithofacies (Gill 1925; Tanton 1925, 1931a; Moorhouse 1960a; Goodwin 1960a).

During the 2022 field season, limited observations of the Gunflint Formation were made. The large exposure on Highway 11–17 that exposes the Kakabeka conglomerate south of Pass Lake also exposes rocks of the lower Gunflint Formation. At this exposure, chloritized Archean felsic to intermediate intrusive rocks are locally overlain by at least 4 stromatolite mounds (Photo 11.1C) comprising thinly laminated black to red chert. The stromatolite mounds have a height of up to 30 to 50 cm and similar widths. The top of one mound is marked by a thin stylolitic band. The areas between stromatolite mounds comprise silicified grainstones that locally contain sulphide nodules up to 5 cm in diameter. The grainstones enclosing the stromatolite form medium to thick beds characterized by medium- to large-scale trough cross-stratification. At this locality, an east-dipping and roughly north-striking small displacement thrust fault puts Archean basement rocks above Gunflint Formation rocks. The fault appears to displace Midcontinent Rift–related quartz-carbonate-sulphide veins indicating that the thrusts may be related to rift inversion; however, this field relationship is equivocal.

Gunflint Formation rocks were also observed in the southwestern portion of the project area. North of North Lake, an exposure of weathered shaley rock approximately 4 to 5 m high contains abundant coarse-grain diagenetic pyrite nodules (Photo 11.1D). Flat exposures of granular iron formation in this general area also locally display abundant carbonate-hematite pisoliths (Photo 11.1E). The presence of both early diagenetic pyrite and early diagenetic carbonate and hematite in the lower Gunflint Formation suggests fluctuations in early diagenetic redox conditions. Northwest of Whitefish Lake, mafic lavas described by previous workers were observed (Gill 1925; Tanton 1931a; Goodwin 1960a) and sampled (Photo 11.1F). The lava flows appear to occur in the upper half of the Gunflint Formation. The thickness of the mafic volcanic unit is difficult to estimate based on the examined exposures. Local red hematite-chert stromatolites were also observed in the Whitefish Lake–Mink Mountain area.

ROVE FORMATION

The Rove Formation has been described in detail by Morey (1969). Based on this work, the Rove Formation in northern Minnesota and Ontario consists of 3 informal units: a lower argillite unit that is 400 feet thick; a transitional unit of interbedded argillite and graywacke, 70 to 100 feet thick; and an upper thin-bedded graywacke as much as 2700 feet thick. In Minnesota, Morey (1969) measured a total thickness for the Rove Formation of at least 3200 feet. In Ontario, Morey (1969) estimated the Rove Formation to be approximately 1900 feet thick in the vicinity of Arrow Lake, which is in the southwestern part of the project area. Tuff horizons near the base of the Rove Formation yielded U/Pb zircon ages of 1827±8 and 1836±5 Ma (Addison et al. 2005). A maximum depositional age for the Rove Formation is 1826.2 Ma±16.1 Ma, an average of the 5 youngest grains in a sandstone sample from the Grand Portage area (Craddock et al. 2013).

Field observations of the Rove Formation during the summer of 2022 were limited to relogging a few cored diamond-drill holes and mapping a few known exposures. Outcrops of the lower Rove Formation near the community of Stanley occur above exposures of the Sudbury impact layer (Addison et al. 2005). Here, the lower Rove Formation is characterized by dark grey to black fissile, thinly laminated shales (Photo 11.2A) without visually abundant sulphides, local large carbonate concretions and local lensoid beds of grey carbonate-rich rock. Outcrop exposures of the middle part of the Rove Formation, and drill core from the middle Rove Formation from several areas, mainly comprise thinly laminated to thinly bedded dark grey to black mudstone and siltstone interlayered with thin- to medium-bedded light grey fine- to medium-grained sandstones (wacke) (Photo 11.2B). Sedimentary structures and soft-sediment deformation features observed in this middle unit include graded bedding, load casts and flame

structures, local mudchip horizons within sandstone beds, parallel lamination and small-scale trough cross-stratification (both current ripples and wave ripples; Photo 11.2C). The upper Rove Formation was observed in drill core, and in limited outcrop exposures. The upper Rove Formation is characterized by the presence of local very thickly bedded graded or ungraded grey medium- to coarse-grained sandstones interlayered with rocks like the middle part of the Rove Formation (Photo 11.2D). Thick sandstones locally display flute marks at their bases. Upper surfaces of thick sandstone beds locally display asymmetrical ripple forms. A sample of a thick sandstone from the upper part of the Rove Formation was collected for laser ablation U/Pb detrital zircon geochronology.

Midcontinent Rift Rocks

Much of the project area is underlain by Midcontinent Rift–related igneous rocks. Recent reviews of the geology, geochemistry and geochronology of these rocks are provided by Bleeker et al. (2020) and Cundari et al. (2022). Only a summary is provided here. Midcontinent Rift–related mafic intrusive units in the project area include the Logan diabase sills, Nipigon diabase sills (restricted to the northeastern part of the project area), Cloud River and Pigeon River diabase dike swarms, the Crystal Lake gabbro and the Riverdale mafic sill. The Devon volcanic rocks (e.g., Tanton 1931b; Cundari et al. 2022) are the only probable Midcontinent Rift–related mafic volcanic rocks in the project area.

The Logan sills are the most extensive Midcontinent Rift–related unit in the project area. Logan sills typically form relatively thin (~tens of metres thick), generally gently southwest-dipping sills that intruded both the Gunflint and Rove formations (e.g., Sutcliffe 1991). Smith and Sutcliffe (1989) suggested the presence of at least 6 discrete sills in the area covered by their mapping. Descriptions of the typical textures and mineralogy of sills in the area are given by Sutcliffe (1991). Based on recent geochronology presented by Bleeker et al. (2020), the Logan sills have an age of 1106.3±2.0 Ma.

The Logan sills display reversed magnetic polarity (e.g., Pesonen 1979) and on regional remnant magnetic intensity maps they appear as magnetic “lows” (Ontario Geological Survey 2015). Comparing OGS geophysical compilations for the area and to existing mapping (Santaguida 2001a, 2001b) reveals that there are several large “high” magnetic anomalies in the central and southwestern parts of the map area that appear to underlie the Logan sills intruded into Rove Formation rocks that occur near surface. The cause of these magnetic anomalies is not well established.

Based on Bleeker et al. (2020), the relatively uncommon northwest-striking reversed polarity Cloud River diabase dikes were emplaced 1109.2±2.9 Ma and, thus, may represent the oldest Midcontinent Rift–related intrusions in the project area. The Pigeon River mafic dikes typically strike northeast and form the dominant intrusive unit in the southeastern part of the map area immediately adjacent to Lake Superior. Again, based on ages reported by Bleeker et al. (2020), the Pigeon River dikes may have been emplaced during multiple pulses over a relatively protracted period from *circa* 1097 to 1094 Ma and the nickel-copper-PGE-chromium mineralized Crystal Lake gabbro was likely emplaced at 1093.2±1.2 Ma.

Limited mapping and sampling of rocks from the Midcontinent Rift was carried out during 2022. A thin (<5 m) gently dipping diabase sill or dike and its upper chill margin was observed to have intruded lower Gunflint Formation rocks in the area north of North Lake. Plagioclase glomeroporphyritic upper portions of a Logan sill and its chilled upper contact were observed north of Arrow Lake (Photo 11.2E). Limited observations and sampling of Pigeon River dikes (Photo 11.2F) were also made while examining Rove Formation exposures near the Canada–USA border. A relatively thick, fine-grained mafic intrusive rock intruded Archean basement rocks in the MC-89-1 drill core (UTM 316715E 5340523N which was drilled in Blake Township) indicating that Midcontinent Rift–related intrusions in the area are not limited to those emplaced into the Animikie Group.



Photo 11.2. Representative photos of the Rove Formation and some Midcontinent Rift–related intrusions in the project area. Photo locations are given as UTM co-ordinates in NAD83. **A)** Thinly laminated black silt and shale of the Lower Rove Formation. Hammer for scale is 33 cm long (UTM 307387E 5357510N, Zone 16). **B)** Primarily thin-bedded, fine- to medium-grained sandstones interbedded with siltstone likely from the middle part of the Rove Formation. Pen for scale is 14 cm (UTM 310716E 5323347N, Zone 16). **C)** Close-up of thin-bedded, fine- to medium-grained sand from the same outcrop as in Photo 11.2B showing distinct ripples within local sand beds. Pen with cap is 17 cm. **D)** Thick-bedded sands separated by beds of fine sand to silt. Some tops of the thicker sand beds display ripples, whereas the bases locally display flute marks. Person for scale is 170 cm tall (UTM 329769E 5337997N, Zone 16). **E)** Top of a diabase sill with glomeroporphyritic plagioclase crystals. Compass for scale is 7.1 cm wide (UTM 691744E E 533457N, Zone 15). **F)** Diabase dike forming "Middle Falls" on the Pigeon River (UTM 304900 5321032, Zone 16).

Archean Rocks

Archean rocks exposed in the project area are mainly Neoarchean and are part of the Wawa–Abitibi terrane and the Quetico Basin (e.g., Stott 2011). In the southern part of the project area, felsic to intermediate intrusive rocks predominate and based on compilation maps (Ontario Geological Survey 2011) consist mainly of massive to foliated tonalite and granodiorite and locally gneissic tonalites. Province-scale compilation maps (Ontario Geological Survey 2011) show metavolcanic, metasedimentary, and mafic to ultramafic intrusive rocks of the Shebandowan greenstone belt and clastic metasedimentary rocks and felsic to intermediate intrusions of the Quetico Basin are present in the northern portion of the project area (*see* Figure 11.1).

Limited observations of Archean rocks in the southwestern part of the map area suggest that the Archean rocks there include a variety of variably deformed tonalitic rocks, some of which containing xenoliths of clastic metasedimentary rocks. These tonalites are locally cut by lamprophyric mafic intrusions. Medium-grained, foliated tonalite from the Archean portion of drill-core MC-89-1 was sampled for ID-TIMS U/Pb geochronology. Chloritized granitoid rocks and local Archean ductile shear zones were observed to underlie the Gunflint Formation–Archean unconformity in exposures south of Pass Lake close to the northeastern boundary of the project area (*see* Photo 11.1A).

ECONOMIC GEOLOGY

The Ontario Mineral Inventory (Ontario Geological Survey 2022) lists 108 occurrences within the project area. These can be subdivided into 3 main types: i) iron occurrences in the Gunflint Formation, ii) orthomagmatic nickel-copper-PGE-chromium deposits related to Midcontinent Rift intrusions and iii) polymetallic vein deposits associated with the Midcontinent Rift. The general distribution of these is shown on Figure 11.1.

Lake Superior-type iron formations within the Gunflint Formation form several known, but thus far subeconomic, iron occurrences and reviews of these are provided by Shklanka (1968) and the Ontario Mineral Inventory (Ontario Geological Survey 2022). Iron occurrences occur mainly along the northern boundary of the Animikie Basin where the Gunflint Formation is exposed on surface.

Nickel-copper-PGE occurrences are relatively common in the project area. Most occur in the southeastern part of the project area (*see* Figure 11.1). The Animikie Basin remains relatively underexplored for its nickel-copper-PGE potential despite significant nickel-copper-PGE deposits in the USA (e.g., the Tamarack and Eagle deposits: e.g., Bleeker et al. 2020) occurring in small intrusions emplaced into the lithostratigraphic equivalents of the Rove Formation.

Proterozoic polymetallic vein deposits (5-element type) were a source of silver and barite production during the late 1800s and occur in 2 main, fault-controlled, groups known as the Mainland and Island belts (cf. Franklin et al. 1986; Sergiades 1968). Production tonnages are summarized by Franklin et al. (1986). Recent exploration of the Beaver Mine discovered several new silver veins along with previously unknown cobalt mineralization (Wray and Yarie 2019). Past-producing deposits are mainly hosted in the Rove Formation; however, mineralization also occurs in veins cutting Gunflint Formation rocks and the Archean basement.

During the field season, several sulphide-bearing veins of the Proterozoic polymetallic type were collected for comprehensive multi-element geochemistry.

FUTURE WORK

Field work on this project is likely to continue for several field seasons. Over the winter of 2022–2023 compilation of existing outcrop data, diamond drilling and geophysical data interpretation is planned. During the field season in 2023, mapping in the previously unmapped southwestern part of the project area, and relogging of drill core will be a major focus.

ACKNOWLEDGMENTS

We would like to thank Fort William First Nation, Métis Nation of Ontario Region 2 Thunder Bay Métis Council, Red Sky Métis Independent Nation and Lac la Croix First Nation for allowing the Ontario Geological Survey to map in their traditional land use area. Their co-operation is greatly appreciated.

We would also like to thank Manuel Duguet, Michael Easton and Monica Gaiswinkler Easton for helpful reviews of this article. Tara Doherty provided excellent field assistance. Thanks to Saurav Biswas for compiling and "relevelling" geophysical data used for preliminary interpretations. Pat Gervais is thanked for figure drafting.

Geological discussions with Mark Puumala, Rob Cundari, Dorothy Campbell, Justin Jonsson, Sophie Kurucz and Greg Paju of the Thunder Bay Resident Geologist Office, Michael Easton (Earth Resources and Geoscience Mapping Section) and Mark Smyk, Phil Fralick, Peter Hollings, Dan Kontak and John Fingas have been invaluable, and we are grateful for them.

REFERENCES

Addison, W.D., Brumpton, G.R., Vallini, D.A., McNaughton, N.J., Davis, D.W., Kissin, S.A., Fralick, P.W. and Hammond, A.L. 2005. Discovery of the distal ejecta from the 1850 Ma Sudbury impact event; Geology, v.33, p.193-196.

Bleeker, W., Smith, J., Hamilton, M.[A.], Kamo, S.[L.], Liikane, D., Hollings, P., Cundari, R.[M.], Easton, [R.]M. and Davis, D.[W.] 2020. The Midcontinent Rift and its mineral systems: Overview and temporal constraints of Ni-Cu-PGE mineralized intrusions; *in* Targeted Geoscience Initiative 5: Advances in the understanding of Canadian Ni-Cu-PGE and Cr ore systems—Examples from the Midcontinent Rift, the Circum-Superior Belt, the Archean Superior Province, and Cordilleran Alaskan-type intrusions, Geological Survey of Canada, Open File 8722, p.7-35.

Bowen, N.L. 1911a. Silver in the Thunder Bay District; Ontario Bureau of Mines, Annual Report, v.20, p.119-132.

——— 1911b. Map of the Silver Mountain area, District of Thunder Bay; Ontario Bureau of Mines, Annual Report Map 20a, scale 1:63 360.

Craddock, J.P., Rainbird, R.H., Davis, W.J., Davidson, C., Vervoort, J.D., Konstantinou, A., Boerboom, T., Vorhies, S., Kerber, L. and Lundquist, B. 2013. Detrital zircon geochronology and provenance of the Paleoproterozoic Huron (~2.4-2.2 Ga) and Animikie (~2.2-1.8 Ga) basins, southern Superior Province; The Journal of Geology, v.121, p.623-644.

Cundari, R., Hollings, P., Smyk, M. and Carl, C. 2022. The geochemical evolution of the Logan igneous suite, Ontario, Canada: New insights from the Logan Basin and implications for the genesis of the Mesoproterozoic Midcontinent Rift System; *in* Large igneous provinces and their plumbing systems, The Geological Society, Special Publication, v.518, p.43-65. doi.org/10.1144/SP518-2021-6

Dematties, T.A. 2022. Exploration-resource assessment of productive felsic volcanic centers in the Paleoproterozoic Penokean Volcanic Belt of northern Wisconsin, Michigan and east-central Minnesota, USA; Ore Geology Reviews, v.141, article 104489.

Fralick, P., Davis, D.W. and Kissin, S.A. 2002. The age of the Gunflint Formation, Ontario, Canada: Single zircon U–Pb age determinations from reworked volcanic ash; Canadian Journal of Earth Sciences, v.39, p.1085-1091.

Franklin, J.M., Kissin, S.A., Smyk, M.C. and Scott, S.D. 1986. Silver deposits associated with the Proterozoic rocks of the Thunder Bay District, Ontario; Canadian Journal of Earth Sciences, v.23, p.1576-1591.

Geul, J.J.C. 1969a. Cloud Bay area (east part), District of Thunder Bay; Ontario Department of Mines, Preliminary Map P.530, scale 1:15 840.

——— 1969b. Cloud Bay area (west part), District of Thunder Bay; Ontario Department of Mines, Preliminary Map P.529, scale 1:15 840.

——— 1970a. Devon and Pardee townships and Stuart Location, Thunder Bay District; Ontario Department of Mines, Map 2207, scale 1:31 680.

——— 1970b. Geology of Devon and Pardee townships and the Stuart Location; Ontario Department of Mines, Geological Report 87, 52p.

Gill, J.E. 1925. Gunflint iron-bearing formation, Ontario; *in* Summary Report for the Year 1924, Part C, Geological Survey of Canada, p.28-88.

Goodwin, A.M. 1956. Facies relations in the Gunflint iron formation; Economic Geology, v.51, p.565-595.

——— 1960a. Gunflint iron formation of the Whitefish Lake area, District of Thunder Bay; Ontario Department of Mines, Annual Report, 1960, v.69, pt.7, p.41-63.

——— 1960b. Whitefish Lake area, Gunflint iron range, District of Thunder Bay; Ontario Department of Mines, Map 1960i, scale 1:31 680.

Ingall, E.D. 1888. Report on mines and mining on Lake Superior; Geological and Natural History Survey of Canada, Annual Report for 1887–1888, v.3, pt.H, p.1-131.

Javaux E.J. and Lepot, K. 2018. The Paleoproterozoic fossil record: Implications for the evolution of the biosphere during Earth's middle age; Earth-Science Reviews, v.176, p.68-86.

Konhauser, K.O., Planavsky, N.J., Hardisty, D.S., Robbins, L.J., Warchola, T.J., Haugaard, R., Lalonde, S.V., Partin, C.A., Oonk, P.B.H., Tsikos, H., Lyons, T.W., Bekker, A. and Johnson, C.M. 2017. Iron formations: A global record of Neoarchaean to Paleoproterozoic environmental history; Earth-Science Reviews, v.172, p.140-177.

Krogh, T.E., Davis, D.W. and Corfu, F. 1984. Precise U–Pb zircon and baddeleyite ages for the Sudbury area; *in* The geology and ore deposits of the Sudbury Structure, Ontario Geological Survey, Special Volume 1, p.431-446.

Moorhouse, W.W. 1960a. Gunflint iron range in the vicinity of Port Arthur, District of Thunder Bay; Ontario Department of Mines, Annual Report, 1960, v.69, pt.7, p.1-40.

——— 1960b. Kakabeka Falls area, Gunflint iron range, District of Thunder Bay; Ontario Department of Mines, Map 1960k, scale 1:31 680.

——— 1960c. Loon Lake area, Gunflint iron range, District of Thunder Bay; Ontario Department of Mines, Map 1960p, scale 1:31 680.

——— 1960d. McIntyre area, Gunflint iron range, District of Thunder Bay; Ontario Department of Mines, Map 1960m, scale 1:31 680.

——— 1960e. Port Arthur area, Gunflint iron range, District of Thunder Bay; Ontario Department of Mines, Map 1960o, scale 1:31 680.

Moorhouse, W.W. and Goodwin, A.M. 1960a. Hymers–Stanley area, Gunflint iron range, District of Thunder Bay; Ontario Department of Mines, Map 1960l, scale 1:31 680.

——— 1960b. Neebing area, Gunflint iron range, District of Thunder Bay; Ontario Department of Mines, Map 1960n, scale 1:31 680.

——— 1960c. Silver Mountain area, Gunflint iron range, District of Thunder Bay; Ontario Department of Mines, Map 1960j, scale 1:31 680.

Morey, G.B. 1969. Stratigraphy and sedimentology of the Middle Precambrian Rove Formation in northeastern Minnesota; Journal of Sedimentary Research, v.37, p.1154-1162.

——— 1983. Animikie Basin, Lake Superior region, U.S.A.; *in* Iron-formations: Facts and problems, Amsterdam, Elsevier, Developments in Precambrian Geology, v.6, p.13-67.

Ojakangas, R.W., Morey, G.B. and Southwick, D.L. 2001. Paleoproterozoic basin development and sedimentation in the Lake Superior region, North America; Sedimentary Geology, v.141-142, p.319-341.

Ontario Geological Survey 2011. 1:250 000 scale bedrock geology of Ontario; Ontario Geological Survey, Miscellaneous Release—Data 126 – Revision 1.

——— 2015. Ontario airborne geophysical surveys, magnetic and gamma-ray spectrometric data, grid and profile data (ASCII and Geosoft® formats) and vector data, Mahon Lake and Flatrock Lake areas; Ontario Geological Survey, Geophysical Data Set 1077.

——— 2022. Ontario Mineral Inventory; Ontario Geological Survey, Ontario Mineral Inventory (September 2022 update), online database.

Pesonen, L.J. 1979. Paleomagnetism of Keweenawan igneous and baked contact rocks from Thunder Bay area, northern Lake Superior; Bulletin of the Geological Society of Finland, v.51, p.27-44.

Poulton, S.W., Fralick, P.W. and Canfield, D.E. 2004. The transition to a sulphidic ocean ~1.84 billion years ago; Nature, v.431, p.173-177.

Pye, E.G. and Fenwick, K.G. 1963. Geological compilation series, Lakehead–Shebandowan Sheet, District of Thunder Bay; Ontario Department of Mines, Preliminary Map P.177, scale 1:126 720.

Santaguida, F. 2001a. Precambrian geology compilation series—Quetico sheet; Ontario Geological Survey, Map 2663, scale 1:250 000.

——— 2001b. Precambrian geology compilation series—Thunder Bay sheet; Ontario Geological Survey, Map 2664, scale 1:250 000.

Schultz, K.J. and Cannon, W.F. 2007. The Penokean orogeny in the Lake Superior region; Precambrian Research, v.157, p.4-25.

Scott, J. 1990. Geology of MacGregor Township; Ontario Geological Survey, Open File Report 5719, 82p.

Sergiades, A.O. 1968. Silver cobalt calcite vein deposits of Ontario; Ontario Department of Mines, Mineral Resources Circular 10, 498p.

Shklanka, R. 1968. Iron deposits of Ontario; Ontario Department of Mines, Mineral Resources Circular 11, 489p.

Smith, A.R. and Sutcliffe, R.H. 1989. Precambrian geology of Keweenawan intrusive rocks in the Crystal Lake–Pigeon River area; Ontario Geological Survey, Preliminary Map P.3139, scale 1:50 000.

Smith, J., Bleeker, W., Liikane, D.A., Hamilton, M., Cundari, R. and Hollings, P. 2019. Characteristics of Ni-Cu-PGE sulphide mineralization within the 1.1 Ga Midcontinent Rift; *in* Targeted Geoscience Initiative: 2018 report of activities; Geological Survey of Canada, Open File 8549, p.421-432.

Stott, G.M. 2011. A revised terrane subdivision of the Superior Province in Ontario; Ontario Geological Survey, Miscellaneous Release—Data 278.

Sutcliffe, R.H. 1991. Proterozoic geology of the Lake Superior area; Chapter 16 *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, p.627-658.

Tanton, T.L. 1925. Eastern part of the Matawin iron range, Thunder Bay District, Ontario; *in* Summary Report for the Year 1924, Part C, Geological Survey of Canada, p.1-27.

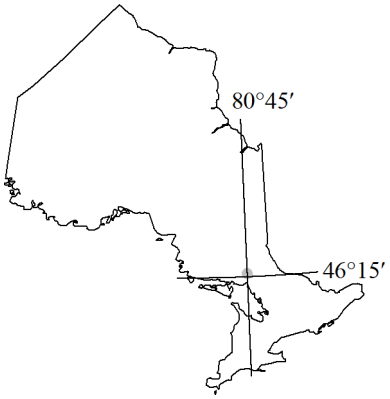
——— 1931a. Fort William and Port Arthur, and Thunder Cape map areas, Thunder Bay District, Ontario; Geological Survey of Canada, Memoir 167, 222p.

——— 1931b. Pigeon River area, Thunder Bay District; Geological Survey of Canada, Map 354A, scale 1:63 360.

Wray, N.P. and Yarie, Q.D. 2019. 2018 Exploration report for the Beaver silver project, Honey Badger Exploration Inc.; unpublished report, Thunder Bay Resident Geologist's office, Thunder Bay South District, assessment file AFRI# 20000017904, 1261p.

Zi, J.W., Sheppard, S., Muhling, J.R. and Rasmussen, B. 2022. Refining the Paleoproterozoic tectonothermal history of the Penokean Orogen: New U-Pb age constraints from the Pembine–Wausau terrane, Wisconsin, USA; Geological Society of America Bulletin, v.134, p.776-790.

12. Project SO-22-003. Geology of the Grenville Front Tectonic Zone near Sudbury, Northeastern Ontario



R.M. Easton[1]

[1]Earth Resources and Geoscience Mapping Section, Ontario Geological Survey

INTRODUCTION

Two current 1:50 000 scale geological compilation maps exist for the Sudbury area: Dressler (1984) and Ames et al. (2005). A notable geoscience gap on the Ames et al. (2005) compilation map is that the southeast corner of the compilation, underlain by rocks of the Grenville Province, is mostly blank. This area covers approximately 60 km^2, and includes parts of Cleland, Dill, Dryden and Secord townships. Although geological units are shown in this area on Dressler (1984), that geological information is from the late 1950s to the late 1960s, well before modern understanding of the geological history of the Grenville Province. Furthermore, since the publication of both Dressler (1984) and Ames et al. (2005), Highway 69 has been four-laned, resulting in the creation of many new roadcuts in the area.

To fill in the gap on the Ames et al. (2005) map, approximately 4 weeks of field work and sampling were conducted in September and October 2021 and in June to August 2022 in an area south, southeast and east of Sudbury (Figure 12.1). Access to the study area is provided by Highways 69 and 537, Estaire Road (old Highway 69) and several local roads. The study area includes the communities of Wanup, Estaire and Wahnapitae. A key question for this project is to determine if rocks of the Huronian Supergroup and/or Nipissing gabbros are present in the Grenville Front tectonic zone (GFTZ). If they are, then the rocks in the GFTZ should be prospective for the same commodities as their counterparts in the Southern Province (especially nickel-copper-platinum group elements (PGE) in the Nipissing gabbros). If not, then what is the origin and exploration potential of the rocks in the GFTZ? This article focusses on these questions.

The study area includes rocks of the Grenville Front tectonic zone and the Nepewassi domain of the Grenville Province (Figure 12.2). The GFTZ includes highly deformed rocks that formed along the leading edge of the Grenville Province as it was thrust northward during the Grenville orogeny, with most of that deformation occurring between 1030 to 990 Ma. The Nepewassi domain is a thrust sheet that moved northward atop of the GFTZ. It contains a mixture of Archean gneisses, Paleoproterozoic and Mesoproterozoic intrusions, and several belts of quartzite. Previous work of relevance in the study area includes Grant et al. (1962), Kwak (1968, 1971), Lumbers (1975) and Vos, Smith and Stevenato (1981). Some preliminary results of this project were presented in Easton (2022).

THE GRENVILLE FRONT TECTONIC ZONE

The Grenville Front tectonic zone (GFTZ) is a region up to 30 km wide present between the Grenville Front and the Central Gneiss Belt of the Grenville Province (*see* Figure 12.1) (Easton 1992, 2000). The GFTZ can be envisaged broadly as an anastomosing network of higher strain rocks,

Summary of Field Work and Other Activities, 2022,
Ontario Geological Survey, Open File Report 6390, p.12-1 to 12-15.

© King's Printer for Ontario, 2022

moderately inclined and shallowing southeastward, surrounding lower strain pods and lenses that are presumably elongate parallel to the prevalent southeast-plunging stretching lineation. The same style of structure can be seen in many places at an outcrop scale. Its southeast margin is ill defined, mainly because of the lack of detailed mapping throughout the GFTZ and the Nepewassi domain.

The Grenville Front Tectonic Zone in the Study Area

Mapping in 2021 revealed that the Grenville Front tectonic zone (GFTZ) in the study area displays different structural styles west and east of the Wanapitei River (Easton 2022). West of the Wanapitei River, units consist mainly of highly strained grey gneisses, typically migmatitic (Photo 12.1A), that form thin, near-continuous belts interlayered with migmatitic amphibolite, amphibolite and garnet amphibolite. These gneisses could represent highly strained Archean bedrock. Possible metasedimentary units, including schists with aluminosilicate minerals, calc-silicate gneisses and minor impure marble (Photo 12.1B), locally form thin, lenticular, discontinuous bands in the package of highly strained gneissic and amphibolitic rocks. Rocks of the East Bull Lake intrusive suite (*circa* 2475 Ma) are present and form thin, discontinuous units. Sudbury swarm (*circa* 1240 Ma) mafic dikes are large, with strike lengths of 50 to 100 m, but are discontinuous. Pegmatite dikes are common on the west side of the Wanapitei River and are predominantly granitic, with some being deformed and concordant or near-concordant with the main foliation. Both narrow (0.5–3.0 m wide) and massive (250 m wide, 2 km long), garnet-bearing, fine-grained leucogranite pegmatites are abundant in the GFTZ (Photos 12.1C and 12.1D)

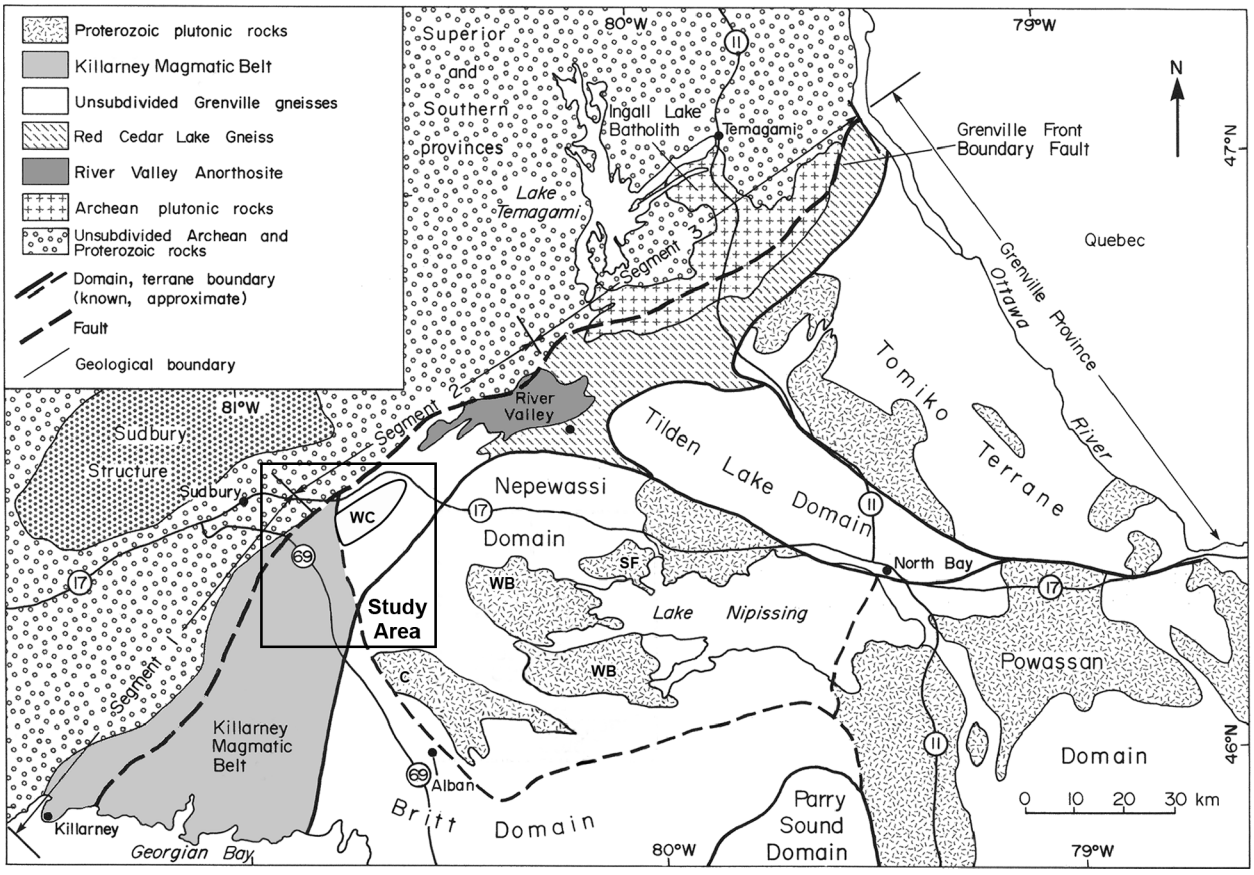


Figure 12.1. Geology of the northern Central Gneiss Belt of the Grenville Province and the Grenville Front region in Ontario. Location of the study area described in this article is indicated. Abbreviations. C – Cosby pluton, SF – Sturgeon Falls batholith, WB – West Bay batholith, WC – Wanapitei complex. Figure *modified from* Easton (1992, p.755).

and were not observed east of the Wanapitei River. Most of the pegmatite dikes, however, are younger than the Sudbury dike swarm and are highly discordant to the main foliation and compositional layering. The boundary of the GFTZ with the Nepewassi domain is only 8 km from the Grenville Front (*see* Figure 12.2).

In contrast, east of the Wanapitei River, several large ovoid plutonic bodies are present, likely related to the Killarney intrusive suite (*circa* 1740 Ma), including the Wanapitei Complex (6 by 2 km) and the Cleland stock (3 by 3 km) (*see* Figure 12.2). East Bull Lake intrusive suite rocks form larger, more

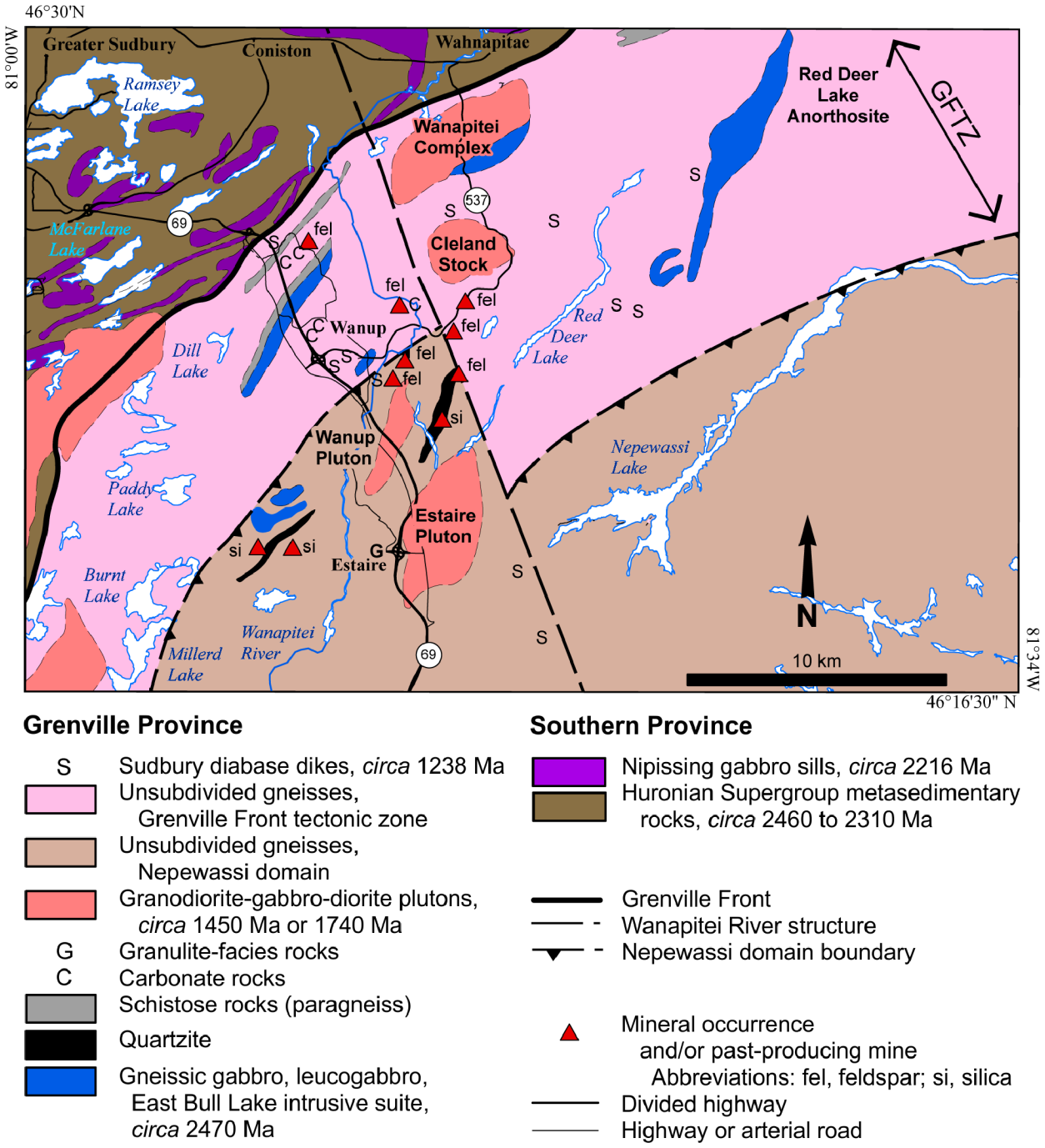


Figure 12.2. Simplified geology of the study area, showing major geological features, industrial mineral occurrences and geological features discussed in the text.

continuous, and better preserved bodies, including the Red Deer Lake intrusion (11 km long, up to 1 km wide). Host gneisses are mostly quartzofeldspathic and contain garnet in both melasome and leucosome (Photos 12.2A, 12.2B and 12.2C), similar to gneisses in Street Township only a few kilometres to the north-northeast. Also present are deformed, lenticular granitoid bodies ("meta-arkoses" of Lumbers 1975; Table 12.1, analysis 1), which define broad folds (*see* maps of Lumbers 1975; Dressler 1984). Similarly, the kyanite-bearing paragneiss units west of Wahnapitae (cf. Grant et al. 1962; Pearson 1959; Easton and James 1997) are more continuous, and better preserved, than possible correlative schistose rocks west of the Wanapitei River. Calc-silicate gneisses and impure marbles have not been reported east of the river. Zones of more highly strained rocks are also present (Photo 12.2D). Sudbury swarm dikes are pod-like, with minimal strike lengths. Late granite pegmatites are less abundant east of the river. The boundary with the Nepewassi domain is approximately 12 to 15 km southeast of Grenville Front (*see* Figure 12.2).

A linear, north-northwest–trending structure associated with the observed lithological differences across the Wanapitei River appears as a weak linear magnetic feature in the low-resolution magnetic data available for the area. The course of the Wanapitei River coincides with this structure from Coniston to

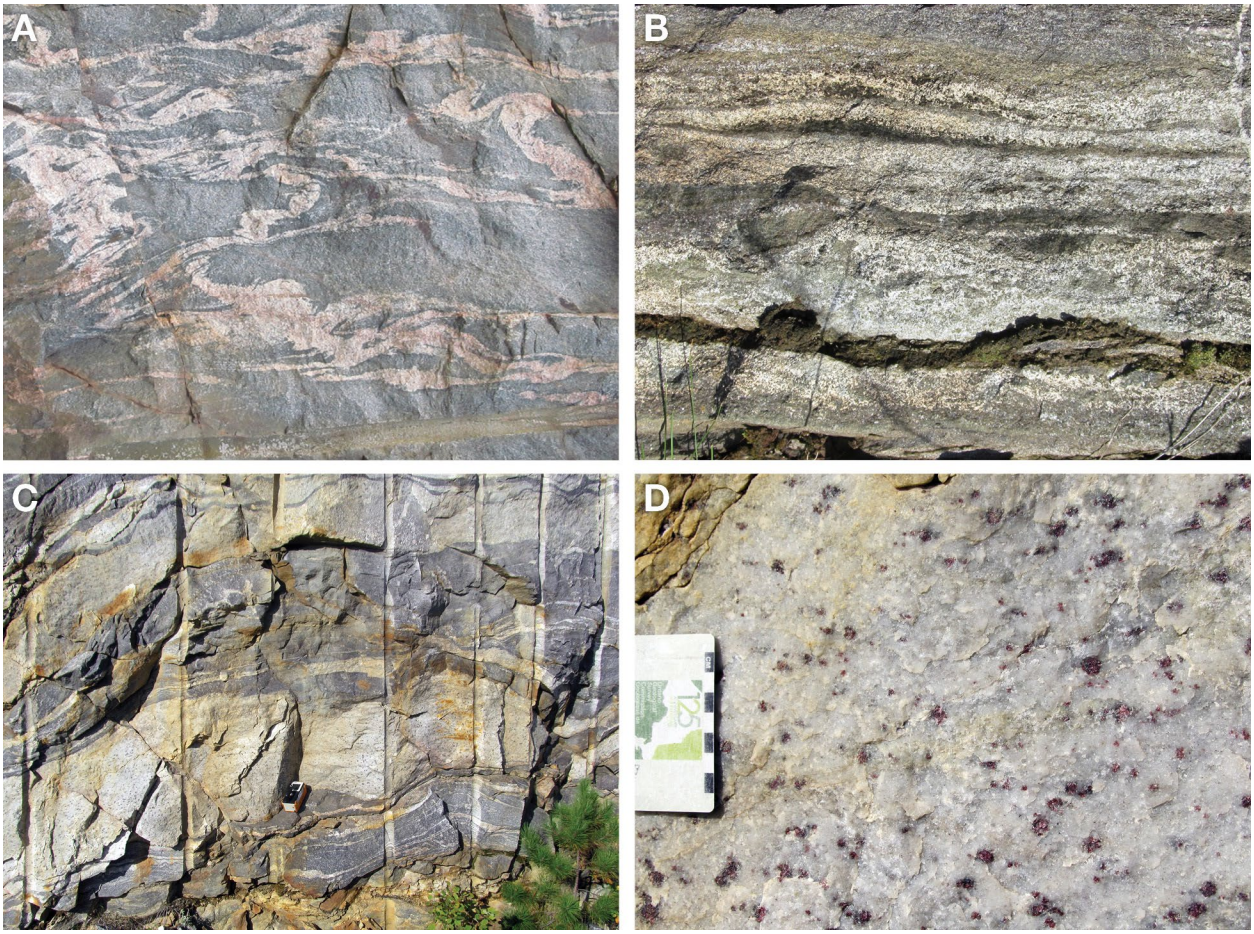


Photo 12.1. Rocks in the Grenville Front tectonic zone west of the Wanapitei River. **A)** Folded granitic leucosome in migmatitic, garnet-bearing, gneissic diorite at north end of the roadcut. Note fabric is oriented vertically, photo has been rotated horizontally to fit in the page. West side of Highway 69/400, 1.8 km from the Grenville Front (UTM 509315E 5141309N). **B)** Impure dolomitic marble and calc-silicate layers in southerly of 2 calc-silicate and marble bands on the west side of Highway 69/400, north side of Old Wanup Road overpass. Scale card is 9 cm long (UTM 510571E 5140422N). **C)** Most of the rock face shown is relatively massive, leucosome-poor migmatitic, garnet-bearing, grey gneissic granodiorite; however, there is a zone that is much more leucosome rich in the lower, centre part of the photo. West side of Highway 69/400 (UTM 5111057E 5137014N). **D)** Close-up of white, garnet-bearing, near-concordant white pegmatite dike shown in Photo 12.1C. Scale card is 9 cm long. Location UTM co-ordinates provided in NAD83 in Zone 17.

Estaire, which obscures direct examination of the rocks immediately adjacent to it. The structure is also apparent in the Bouguer gravity data, separating a broad gravity high east of the river from an area of lower density rocks to the west, even though many of the mafic and granulite facies rocks exposed on surface west of the Wanapitei River have specific gravity values of 3.0 to 3.2 g/cm^3. Based on the gravity data, the structure may be dipping moderately to the west.

The structure coincides with a regional flexure in the trace of the GFTZ, from north-northeast from Killarney to Wanup, to northeast from Wanup eastward. A preliminary explanation for the lithological and structural differences across the Wanapitei River structure is that different structural levels are exposed on either side, with a likely deeper, and possibly hotter, level preserved on the west side. The greater degree of migmatization in rocks within the GFTZ, and the presence of granulite-facies rocks in the Nepewassi domain west of the Wanapitei River (Easton 2022), are both consistent with higher temperatures. Regardless, more work is needed to understand the origin and history of this structure.

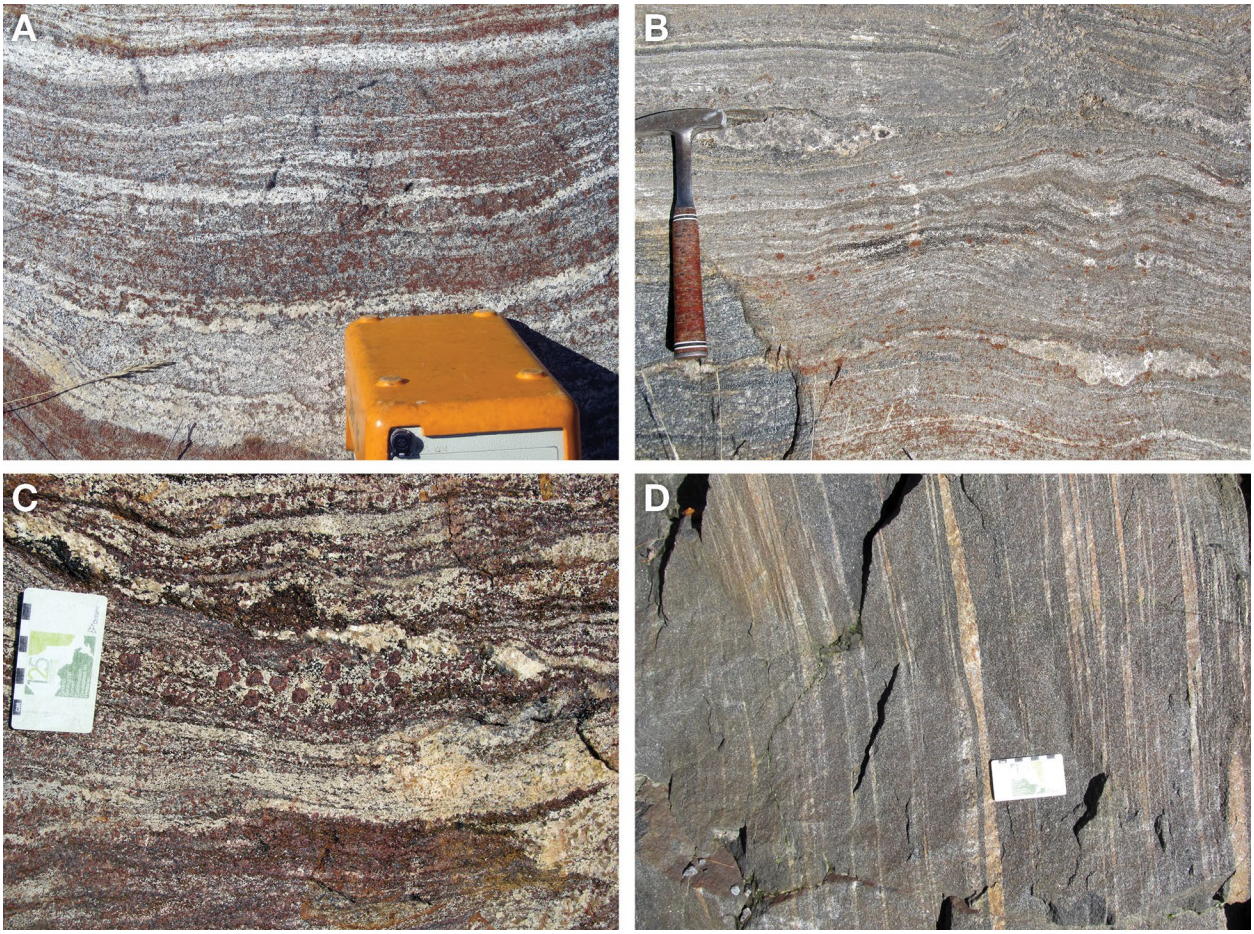


Photo 12.2. Rocks of the Grenville Front tectonic zone east of the Wanapitei River. **A)** Stomatic garnet-bearing felsic metatexite gneiss at this station. Outcrop is on the west side of St. Cloud Road (UTM 515544E 5138949N). Scintillometer for scale, instrument is 23 cm long, back of scintillometer is 10 cm square. **B)** Stomatic felsic metatexite gneiss. Outcrop is on the west side of St. Cloud Road. Hammer for scale, handle is 33 cm long. **C)** Deformed, migmatitic gneiss showing a garnet dispersed throughout the rock. Scale card is 9 cm long. From a roadcut on Highway 537 (UTM 515699E 5137741N). **D)** North-facing, vertical face of typical highly strained gneiss exposed along Highway 537 (UTM 517896E 5133444N). Scale card is 9 cm long. Location UTM co-ordinates provided in NAD83 in Zone 17.

Table 12.1. Summary of geochemical data from metamorphosed igneous rocks from the study area. Work was performed at the OGS Geoscience Laboratories.

Analysis Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Sample Number	**21RME -075**	**21RME -021**	**21RME -022**	**21RME -020**	**19RME -2008**	**21RME -066**	**21RME -027**	**21RME -062**
Easting [a] (m)	511542	514042	5129235	514042	512277	509975	509443	509861
Northing [a] (m)	5136652	5129295	5129037	5129295	5137074	5139759	5139333	5140409
Unit	MA	EP	EP	EP	n/a	EBLI	Type-1	Type-2
Rock Name	gneissic granite	gneissic megacrystic granodiorite	gneissic megacrystic granodiorite	gneissic diorite	garnet amphibolite	garnet leuco-amphibolite	garnet amphibolite	garnet amphibolite
SiO_2 (wt %)	67.25	61.72	62.59	51.72	41.91	47.78	49.45	50.72
TiO_2	0.48	0.92	0.95	0.74	0.99	0.76	0.86	1.35
Al_2O_3	16.74	15.40	15.13	15.69	19.86	19.99	15.36	15.89
$Fe_2O_3^{total}$	2.89	8.76	7.83	10.51	16.90	10.49	13.47	14.22
MnO	0.068	0.162	0.156	0.166	0.154	0.149	0.216	0.190
MgO	0.92	0.99	1.40	5.79	7.30	5.16	7.60	4.96
CaO	1.712	3.414	3.556	8.903	11.31	12.112	9.543	9.695
Na_2O	3.49	3.43	3.41	3.71	0.95	2.69	1.48	0.98
K_2O	5.44	3.37	3.18	1.39	0.52	0.49	0.91	0.63
P_2O_5	0.116	0.257	0.303	0.220	0.024	0.075	0.108	0.181
CO_2	0.133	0.20	0.059	0.430	0.312	0.061	0.06	0.141
S	<0.003	0.059	0.054	0.103	0.306	0.022	0.131	0.274
LOI	0.60	0.14	0.33	0.66	0.58	0.45	0.79	0.48
Ba (ppm)	1282	2265	1996	666	131	73	123	150
Rb	130.9	60.0	56.8	44.4	14.6	8.6	17.4	9.2
Sr	519	370	384	434	551	209	116	35
V	29	28	46	218	774	225	268	292
Pb	25	17	15	12	<1.7	7	9	2
Th	10.3	4.1	4.3	3.4	0.28	<1.9	<1.9	2.9
U	1.3	<1.3	<1.3	<1.3	0.16	<1.3	<1.3	<1.3
Nb	12.0	15.7	24.4	15.1	<0.7	3.1	3.5	7.3
Y	18.7	32.0	31.7	47.2	3.9	17.2	21.9	37.1
Zn	59	138	119	119	92	80	105	126
Zr	232	743	541	46	11	56	60	143
Ni	3	5	6	37	40	51	127	6
Cr	<7	12	11	22	58	125	221	101
Cu	2	25	17	46	167	231	106	188
Au (ppb)	<0.6	1.7	0.9	2.7	2.3	2.5	<0.6	<0.6
Pd (ppb)	<0.14	0.18	0.14	<0.14	0.23	15.3	4.9	0.94
Pt (ppb)	<0.06	0.19	0.16	0.12	0.28	13.1	7.1	1.52
TREE (ppm)	223	221	205	212	18.7	48	48	113

[a] Universal Transverse Mercator (UTM) co-ordinates provided in North American Datum 1983 (NAD83) in Zone 17.

Notes: *Major element oxides are in weight % (wt %); trace element data are in parts per million (ppm), except for Au, Pd, Pt which are in parts per billion (ppb).*

Abbreviations*: EBLI, East Bull Lake intrusive suite; EP, Estaire pluton; LOI, loss-on-ignition; MA, "meta-arkose" of Lumbers (1975); n/a, not applicable; nr, not reported; TREE, total rare earth element.*

Nepewassi Domain

The Nepewassi domain (Easton 1992) was defined based on structural trends and rock types. The area underlain by the Nepewassi domain in the study area was mapped by Lumbers (1975) at a scale of 1:126 720. The Nepewassi domain is underlain by compositionally heterogeneous migmatitic gneisses that have a polycyclic history. Plutonic rocks in the domain form 2 suites that are less deformed than their typically migmatitic host rocks (Lumbers 1975): an older, granite-monzogranite suite (*circa* 1740 Ma) and a younger, non-migmatitic suite (*circa* 1460 to 1420 Ma), that includes the Chief Lake granite and the Cosby pluton. Both plutonic suites represent an eastward continuation into the Grenville Province of the main igneous components of the Killarney Magmatic Belt (cf. Easton 2014). Near Alban, the Cosby pluton intruded a thick sequence of quartzite, known as the French River quartzite (cf. Lumbers 1975; Krogh 1989). Leucogabbro to anorthosite of the St. Charles and Mercer intrusions occur in the western part of Nepewassi domain and were emplaced at *circa* 1225 Ma (Prevec 2004).

The most significant new observation from the northwestern Nepewassi domain in the study area is the identification of granulite-facies, green and pink, garnet-bearing, potassium feldspar megacrystic granodioritic gneiss (*see* Table 12.1: analyses 2 and 3), and incorporated pods of hypersthene-bearing gneissic diorite (*see* Table 12.1: analysis 4), a likely co-magmatic phase, in the Estaire pluton. These rocks are well exposed on Nelson Road west of Estaire (Easton 2022: Stop 7), 14 km south of the Grenville Front and 6 km south of the northern margin of Nepewassi domain. In thin section, orthopyroxene occurs in the gneissic diorite, along with clinopyroxene-garnet [$Alm_{58}Adr_{2}Grs_{18}Prp_{19}Sps_{4}$]-hastingsite-biotite (4.5 weight % TiO_2) and andesine. Opaque minerals are pyrrhotite and pyrite. Orthopyroxene is locally altered to calcite and is the only mafic phase that shows alteration. The presence of orthopyroxene indicates that this rock reached temperatures of at least 800°C (Pattison et al. 2003). The overall mineralogy of the green and pink granodioritic gneiss is similar, but there are a few key differences. In the green rock, garnet [$Alm_{66}Adr_{3}Grs_{21}Prp_{7}Sps_{4}$] is abundant, occurring primarily along the margins of potassium feldspar megacrysts. Amphibole is hastingsite, plagioclase is oligoclase, potassium feldspar contains 1.3 to 1.9 weight % BaO, and biotite contains 3 to 5 weight % TiO_2. Both magnetite and ilmenite are present, no sulphide minerals or allanite were observed. In contrast, in the pink rock, garnet [$Alm_{67}Adr_{2}Grs_{20}Prp_{10}Sps_{2}$] is sparser, and plagioclase phenocrysts have andesine cores and oligoclase rims. Opaque minerals are ilmenite (stoichiometric) and minor pyrrhotite and pyrite, and allanite, are also present.

The Estaire pluton granodiorites are characterized by high barium (>2000 ppm Ba) and high zirconium (>500 ppm Zr) contents (*see* Table 12.1: analyses 2 and 3), similar to those found in the West Bay pluton, south of Verner. Similar potassium feldspar megacrystic granodioritic gneiss constitutes the smaller Wanup pluton located 6 km north of the community of Estaire (*see* Figure 12.2). The Wanup pluton lacks evidence of granulite-facies metamorphism, which may reflect its higher degree of deformation and its proximity to the GFTZ, only 1 km to the north. Geochemical work on the Wanup pluton is in progress. The potassium megacrystic granodiorite and fine-grained dioritic rocks found in the Estaire and Wanup plutons are typical of Killarney intrusive suite rocks and are also present in eastern Nepewassi domain (cf. Easton 2014). Geochronological work on a sample from the Estaire pluton on Nelson Road is in progress.

In addition, quartzite horizons, possibly correlative with the French River quartzite, occur as 2 discontinuous belts in Secord and Cleland townships. The larger of the 2 belts is 2.2 km long, up to 300 m wide, and occurs on the south side of the Wanapitei River, only 2.2 km south of the boundary with the GFTZ (*see* Figure 12.2). An analysis of this quartzite is provided in Table 12.2 (analysis 6), and a sample was collected for detrital zircon study. A second belt (*see* Figure 12.2), approximately 1.5 km long and up to 150 m wide occurs northeast of Horseshoe Lake in Secord Township.

Table 12.2. Summary of geochemical data from supracrustal from the study area, as well as average samples of the McKim Formation. Analysis 1 *from* Card, Innes and Debicki (1977, Table 8, p.40); analysis 2 *from* Kwak (1968, 1971); analysis 3 from a McKim Formation schist in Hallam Township near Massey. Work on analyses 3 to 8 was performed at the OGS Geoscience Laboratories.

Analysis Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Sample Number	**Average of 8 samples**	**Average of 14 samples**	**21RME -110**	**21RME -029**	**21RME -030**	**21RME -102**	**21RME -054**	**21RME -067**
Easting [a] (m)			429332	509443	509401	513333	510618	510563
Northing [a] (m)			5123814	5139333	5139388	5134250	5138049	5138009
Rock Name	semi-pelite	schist	schist	schist	schist	quartzite	impure marble	calc-silicate gneiss
SiO_2 (wt %)	57.90	59.20	56.28	50.61	55.01	90.75	15.80	65.23
TiO_2	0.83	1.11	1.04	1.53	1.36	0.38	0.34	0.40
Al_2O_3	21.94	20.75	24.46	22.24	21.93	5.09	7.64	9.01
$Fe_2O_3^{total}$	8.10	8.54	7.17	9.50	6.83	0.38	3.73	3.64
MnO	0.06	0.08	0.066	0.106	0.06	0.002	0.178	0.117
MgO	2.93	2.90	1.98	3.74	2.91	0.33	21.08	5.12
CaO	1.01	1.34	0.406	0.459	0.467	0.028	19.498	11.414
Na_2O	1.29	1.49	1.01	0.56	0.69	0.14	0.14	0.45
K_2O	2.77	3.25	3.54	7.42	7.00	1.61	1.88	1.96
P_2O_5	0.12	0.15	0.109	0.147	0.125	0.02	0.086	0.126
CO_2	0.11	nr	0.319	0.99	0.110	0.074	27.25	1.863
S	nr	nr	0.048	0.174	0.105	0.035	0.015	<0.003
LOI/H_2O^+	3.20	1.56	3.58	2.98	2.83	0.90	29.71	2.82
CIA	81.57	77.34	84.93	73.48	74.00	77.04	n/a	42.96
Ba (ppm)			601	1802	1968	95	93	527
Rb			148.0	197.0	196.8	47.7	86.3	52.6
Sr			212.2	57.7	68.7	39.3	87.0	366.0
Ga			34.6	30.6	30.2	5.6	11.9	11.6
V			203	283	261	11	32	8
Pb			31	16	15	3	7	11
Th			16.0	13.8	11.2	<1.9	<1.9	8.9
U			4.3	4.4	3.2	<1.3	1.7	2.4
Nb			14.0	15.8	13.8	0.8	4.9	8.0
Y			31.9	45.9	34.5	4.8	18.9	24.5
Zn			197	721	681	6	140	72
Zr			196	258	200	82	97	211
Ni			74	92	81	9	11	3
Cr			151	184	150	37	19	13
Cu			45	217	166	3	7	<2
Ni/Co			1.63	0.42	0.49	2.97*	n/a	n/a
Cr/Zn			0.77	0.26	0.22	5.97*	n/a	n/a
Au (ppb)			5.6	3.8	1.4	<0.6	<0.6	<0.6
Pd (ppb)			5.7	8.3	7.5	0.22	0.67	0.21
Pt (ppb)			5.9	9.0	7.4	0.2	0.72	0.26
TREE (ppm)			146	202	206	32	103	170

[a] Universal Transverse Mercator (UTM) co-ordinates provided in North American Datum 1983 (NAD83) in Zone 17.

Notes: *Major element oxides are in weight % (wt %); trace element data are in parts per million (ppm), except for Au, Pd, Pt which are in parts per billion (ppb). * indicates Ni/Co or Cr/Zn with Archean ratios.*

Abbreviations*: CIA, chemical index of alteration of Nesbitt and Young (1982); LOI, loss-on-ignition; n/a, not applicable; nr, not reported; TREE, total rare earth element.*

DISCUSSION

Mafic Rocks

Mafic rocks of basaltic composition, now amphibolite, biotite amphibolite and/or mafic gneiss, occur throughout the GFTZ in the study area, but are especially abundant in the area west of the Wanapitei River. Some are strongly migmatitic (>10% leucosome), whereas others are weakly migmatitic to non-migmatitic (1–5% leucosome), Many are garnet bearing, with garnet being a late-forming mineral with respect to the metamorphic history. Regardless of metamorphic state, geochemically the mafic rocks fall into 2 groups based on trace and rare earth element (REE) compositions; hereafter referred to as type-1 and type-2. Type-1 mafic rocks are the more common (*see* Table 12.1: analysis 7), and have near flat REE patterns at 10 to 30 times chondrite-normalized values, with very slight light REE enrichment and negligible europium anomalies (Figure 12.3A). Type-1 mafic rocks includes rocks that texturally, and on the basis of major element geochemistry, can be assigned to the East Bull Lake intrusive suite (*see* Table 12.1: analysis 6). Type-2 mafic rocks (*see* Table 12.1: analysis 8), have sloping REE patterns with strong light REE enrichment at 30 to 100 times chondrite-normalized values, along with slight europium depletion, and with higher contents of high field strength elements than the type-1 mafic rocks (*see* Figure 12.3A). Further geochemical study of these mafic rocks, based on sampling during the 2022 field season, will help confirm these preliminary geochemical observations.

Previous workers (e.g., Lumbers 1975; Dressler 1984; Ames et al. 2005) have generally assigned most of the larger belts of metamorphosed mafic rocks in the GFTZ in the study area to the Nipissing intrusive suite, mainly on textural grounds and proximity to the Southern Province. Based on the geochemical data collected to date as part of this project, mafic rocks with geochemical affinities to the Nipissing intrusive suite have yet to be identified in the study area. Weakly migmatitic mafic rocks on both sides of the Wanapitei River appear to be part of the East Bull Lake intrusive suite based on textural and geochemical similarities. Easton and Murphy (2002) suggested that more strongly migmatitic mafic rocks in the GFTZ in Street Township, immediately northeast of the study area, may be Archean. This may also be the case for the more highly migmatitic mafic rocks in the study area.

Schists (McKim Formation?)

Kwak (1968) identified 2 linear belts of mica-rich schists in the area west of the Wanapitei River (*see* Figure 12.2). The more southerly, but larger (up to 900 m wide) and more continuous (9 km long), belt trends northeast from Dill Lake toward the Wanapitei River, and is exposed on both Estaire Road and Highway 69. The more northerly belt is discontinuous and trends northeast, approximately 3.5 km, from the Pine Grove Golf Club to Alice Lake, with a few small exposures present on Estaire Road. The schists are typically bound to the north and the south by garnet amphibolite. The pelitic and semi-pelitic schists that are the main rock types in both belts consist predominantly of muscovite-quartz-plagioclase, but layers in the schists may also contain garnet, sillimanite, kyanite, potassium feldspar and/or plagioclase porphyroblasts and, as first reported by Easton (2022), staurolite porphyroblasts.

An approximately 80 m long roadcut on Estaire Road studied as part of this project is representative of the schist unit. The southern end of the roadcut consists of weakly migmatitic, garnet amphibolite (*see* Table 12.1: analysis 7), which is in sharp contact with the schists that constitute the bulk of the outcrop. There are at least 3 schist units in the roadcut, which from south to north, are

- biotite-garnet schist with boudinaged quartz layers (quartz veins?)
- muscovite-garnet schist with andesine porphyroblasts and intercalated with thin layers of semi-pelite to psammite (*see* Table 12.2: analysis 4). Garnet [$Alm_{75}Adr_{0}Grs_{7}Prp_{14}Sps_{5}$]

- muscovite-staurolite-garnet schist (*see* Table 12.2: analysis 5) with andesine porphyroblasts. Staurolite is black on the weathered surface and is best seen on slabbed surfaces. Garnet [$Alm_{76}Adr_{1}Grs_{6}Prp_{9}Sps_{5}$]

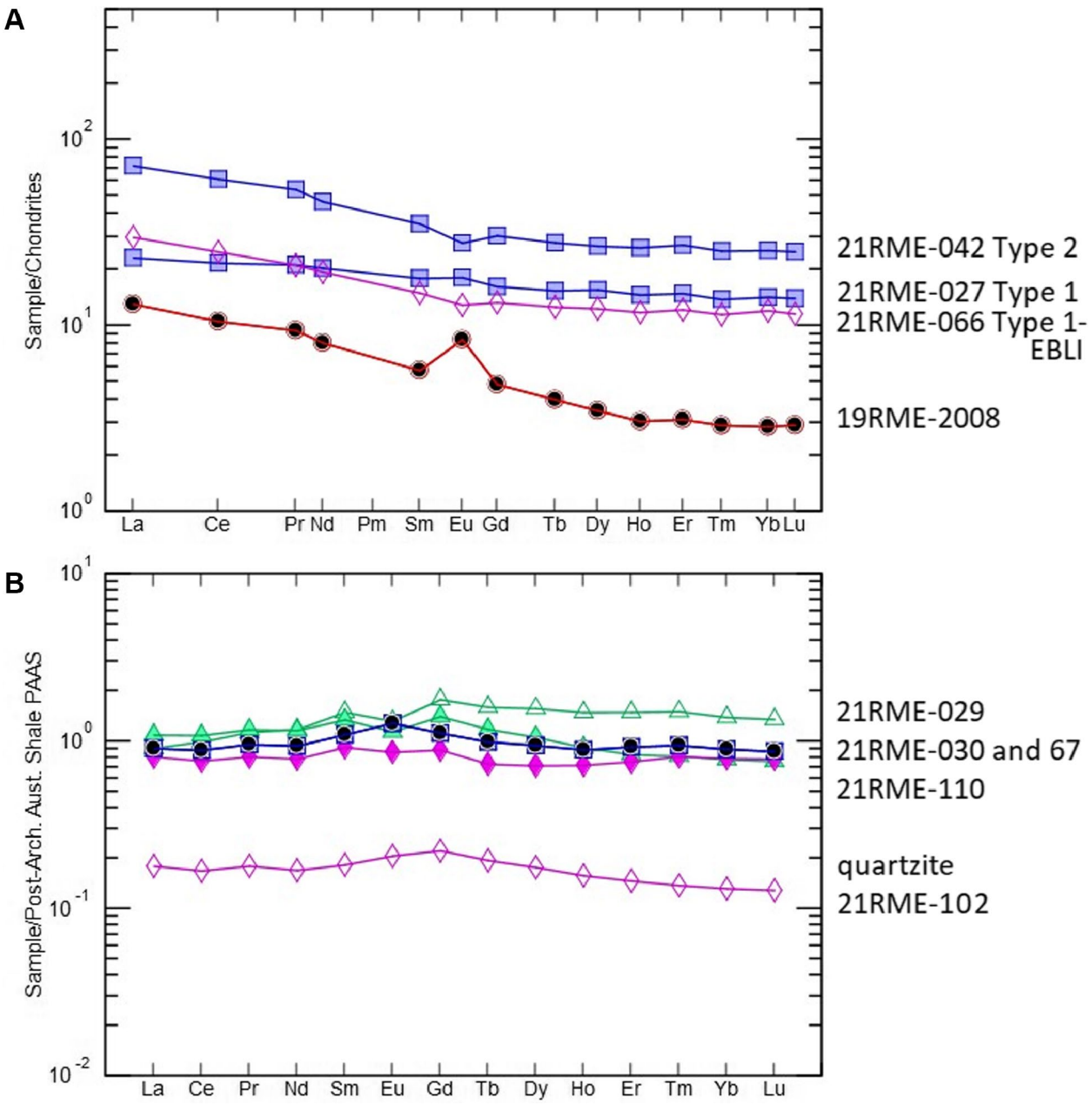


Figure 12.3. A) Primitive mantle chondrite-normalized rare earth element plots for representative mafic rocks from the Grenville Front tectonic zone in the study area. Chemical data for the samples shown are provided in Table 12.1. *See* text for discussion. Normalizing values of Sun and McDonough (1989) were used. **B)** Post-Archean Australian Shale (PAAS) composite-normalized rare earth element plots for representative schist, calc-silicate and quartzite samples from the study area. Chemical data for the samples are given in Table 12.2. *See* text for discussion. Note sample 21RME-067 is a calc-silicate; sample 21RME-110 is from the McKim Formation in Hallam Township near Massey. Normalizing values of Taylor and McLennan (1985) were used.

The aluminous mineralogy present in the schists (muscovite, aluminosilicate minerals) suggests that they could be derived from mudstones of the McKim Formation of the Huronian Supergroup, which typically have aluminum contents greater than 20 weight % (*see* Table 12.2: analyses 1 and 2). If one compares analyses 3, 4 and 5 in Table 12.2, all have aluminium contents greater than 21 weight %, as well as high gallium (>30 ppm), zinc and precious metal contents, indicating that the schists have the geochemical characteristics of McKim Formation mudstones. Rare earth element (REE) patterns for these rocks are inconclusive (*see* Table 12.2: analyses 4 and 5), as they have patterns consistent with the post-Archean Australian shale composite (Figure 12.3B; Taylor and McLennan 1985), but also with the pattern found in FIII rhyolites (Lesher et al. 1986) associated with volcanogenic massive sulphide (VMS) systems.

If these schists are part of the McKim Formation, this is only possible if the McKim Formation has undergone extreme tectonic thinning (from approximately 1 km thick immediately north of the Grenville Front to approximately 100 m to the south). Furthermore, the expected adjacent sandstone-dominated Mississagi and Matinenda Formations, are nowhere to be seen. This assumes, of course, no change in original depositional setting on either side of the Grenville Front. It is possible that some of the neighbouring mafic host rocks are metamorphosed Huronian Supergroup volcanic rocks, but that has yet to be demonstrated. Alternatively, the schists could represent metamorphosed hydrothermally altered rocks similar to those present in VMS systems.

Another possibility is that the schists are indeed part of the McKim Formation, but that they were deposited in a different tectonic setting, perhaps a more distal offshore setting on a rifted continental margin. This could explain their proximity to possible Archean orthogneisses, slivers of East Bull Lake intrusive suite mafic rocks, and the absence of the abundant sandstone units of the Huronian Supergroup.

Carbonate and Calc-silicate Rocks

As noted by Grant et al. (1962) and Kwak (1968) several exposures of carbonate rocks occur in the GFTZ west of the Wanapitei River (*see* Figure 12.2). As part of this study, carbonate rocks were observed and sampled at 6 localities along both Highway 69 and Estaire Road. In all instances, the carbonate rocks occur as thin (30–60 cm wide) bands consisting of impure dolomite and dolomitic marbles, sometimes layered, and associated with 50 to 80 cm wide layers of calc-silicate gneisses. The calc-silicate gneisses consist predominantly of diopside, although phlogopite, fluorapatite, epidote, titanite, zircon, chalcopyrite and/or pyrite may also be present. At all 6 localities, the marbles and the calc-silicate gneisses are hosted in migmatitic gneisses of intermediate composition (i.e., granodiorite), which appear to be of an igneous (orthogneiss) rather than a sedimentary (paragneiss) protolith. None of the occurrences are proximal to the aforementioned Nepewassi domain quartzites or GFTZ schist localities. In terms of chemistry, both the marbles (*see* Table 12.2: analysis 7) and the calc-silicate rocks (*see* Table 12.2: analysis 8) have REE patterns similar to average continental crust (*see* Figure 12.3B), and are unlike typical metamorphosed marbles from the Central Metasedimentary Belt of the Grenville Province (cf. Easton 1995). Although it is tempting to think of these carbonate rocks as being of supracrustal origin, given their discontinuous nature and thinness, their chemistry, and their occurrence in host rocks that are likely originally igneous in origin, an alternate explanation is that they represent channels along which CO_2-rich fluids were transported. These fluids could be derived either from granulite-facies metamorphism, which has been documented in the area, or they could be related to deep-seated carbonatitic magmatism.

ECONOMIC GEOLOGY

Grenville Front Tectonic Zone

EAST BULL LAKE INTRUSIVE SUITE ROCKS

Intrusions of the East Bull Lake intrusive suite present in both the Southern and Grenville provinces locally host platinum-group element mineralization, especially along the margins of the intrusions (cf. James et al. 2002). Despite the high-grade metamorphism of the rocks of the GFTZ west of the Wanapitei River, chemical analyses indicate that all sampled East Bull Lake intrusive suite rocks contain elevated precious metal contents typical of the intrusive suite (*see* Table 12.1: analysis 6). Thus, rocks of the East Bull Lake intrusive suite throughout the study area are exploration targets, especially the larger bodies east of the Wanapitei River.

MAFIC ROCKS

The mineral potential of the other mafic rock units in the GFTZ, especially the more strongly migmatitic units, is more difficult assess. A notable exception is a 300 m thick zone of garnet amphibolite exposed on both sides of Highway 537 near Wanup, centred on UTM 512300E 5137070N. This amphibolite contains 25 to 35% garnet, typically 2 to 5 mm in size. The unusual chemical composition of this rock (*see* Table 12.1: analysis 5; Figure 12.3A: sample 19RME-2008) reflects this high garnet content, and suggests derivation from a previous altered rock, either representing a restite from partial melting or a metamorphosed hydrothermally altered rock similar to those present in a VMS system. This rock may be suitable for industrial mineral purposes as a garnet source, and/or may be useful in targeting possible sulphide mineralization along strike.

PEGMATITES

As noted by Lumbers (1975), 2 types of pegmatite intrusions occur in the study area. The first type consists of gneissic, deformed, leucocratic granitic pegmatite intrusions composed mainly of quartz, plagioclase and potassium feldspar with minor garnet, mica and amphibole. These occur as discontinuous concordant dikes and sills that vary in size from 30 to 50 cm thick to large bodies that are 150 m wide and up to 1 km long. These gneissic pegmatite intrusions are most common in the GFTZ west of the Wanapitei River, and regardless of size, are characterized by anomalous uranium contents (>15 ppm U, or 2–3× average crustal values), but with thorium contents (10–20 ppm Th) similar to average crust (Kyser and Cuney 2009). The anomalous uranium contents in these sheared pegmatites make them unfavourable targets for aggregate or other industrial mineral extraction purposes.

The age of these sheared pegmatites is uncertain, and it is possible that they may have been emplaced at more than one time. Zircon from one of these intrusions in Cleland Township, east of the Wanapitei River, yielded an age between 1600 and 1700 Ma (Krogh and Davis 1970; Lumbers 1975), suggesting an affiliation with the Killarney intrusive suite. In contrast, monazite from one of these intrusions in Dill Township in the GFTZ near the Nepewassi domain boundary yielded a preliminary age of 1390 Ma (Kamo 2022), suggesting an affiliation with the Chief Lake granite (*circa* 1460 Ma). Zircon from the same intrusion as the monazite has yet to be analyzed.

The second type of pegmatite intrusion is more common, and consists of late, post-metamorphic granitic pegmatite intrusions (*circa* 1000 Ma) that are distinctly zoned, commonly with quartz-rich cores and muscovite-rich rims. Some are locally radioactive because of the presence of allanite. The largest of these bodies occur in a 2 km wide zone on either side of the Wanapitei River structure, where many were

quarried in the past, mainly for feldspar and/or mica (Vos, Smith and Stevenato 1981). Ercit (1999) demonstrated that most of the late granitic pegmatites in the northern Grenville Province, regardless of age, are niobium-yttrium-fluorine (NYF) type pegmatites with no associated parental granite, indicating an anatectic origin and post-kinematic emplacement. Such pegmatites are unfavourable targets for lithium exploration, but may be of interest to mineral collectors.

Nepewassi Domain

HIGH-PURITY SILICA

Both quartzite belts in the study area have been either exploited or explored as sources of silica flux, primarily for use as smelter flux, although high-purity silica can be used in a variety of other applications (McAuley 1996). A quarry operated between 1900 and 1923 in Dill Township adjacent to the Canadian Pacific rail line just east of the Wanapitei River and produced silica flux for the nickel industry (Hewitt 1963, p.16; MDI41I07SW000002). This quarry is now water filled. The second site occurs in Secord Township (MDI41I07SW000006, MDI4107SW000003) and has been extensively explored (*see* summaries in McAuley (1996, p.316-322) and Lyon and Jobin-Bevans (2001)), with the southern zone of the property showing the most promise (Lyon and Jobin-Bevans 2001). An initial chemical analysis gave silica values of 98.2 weight % SiO_2 and 0.06 weight % Fe_2O_3 (Hewitt 1963, p.15), with an additional 30 analyses summarized in Lyon and Jobin-Bevans (2001) confirming the high-purity character of the quartzite, with quartz content ranging from 95.5 to 99.0 weight % SiO_2.

ACKNOWLEDGMENTS

J.E. Chartrand provided excellent assistance in the field during both the 2021 and 2022 field seasons. J.E. Chartrand and P. Gervais assisted with the figures in this report. S.A. Clarke of the OGS Geoscience Laboratories assisted with scanning-electron microscope studies of samples from the study area in April and May 2022. This article has benefitted from discussions with M. Duguet and the participants on Field Trip 2 of the 68th Annual Meeting of the Institute on Lake Superior Geology in May 2022.

REFERENCES

Ames, D.E., Davidson, A., Buckle, J.L. and Card, K.D. 2005. Geology, Sudbury bedrock compilation, Ontario; Geological Survey of Canada, Open File 4570, scale 1:50 000.

Card, K.D., Innes, D.G. and Debicki, R.L. 1977. Stratigraphy, sedimentology, and petrology of the Huronian Supergroup in the Sudbury–Espanola Area; Ontario Division of Mines, Geoscience Study 16, 99p.

Dressler, B.O. 1984. Sudbury geological compilation; Ontario Geological Survey, Map 2491, scale 1:50 000.

Easton, R.M. 1992. The Grenville Province; Chapter 19 *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 2, p.713-904.

——— 1995. Regional geochemical variation in Grenvillian carbonate rocks: Implications for mineral exploration; *in* Summary of Field Work and Other Activities, 1995, Ontario Geological Survey, Miscellaneous Paper 164, p.6-18.

——— 2000. Variation in crustal level and large-scale tectonic controls on rare-metal and platinum-group element mineralization in the Southern and Grenville provinces; *in* Summary of Field Work and Other Activities, 2000, Ontario Geological Survey, Open File Report 6032, p.28-1 to 28-16.

——— 2014. Geology and mineral potential of the Nepewassi domain, Central Gneiss Belt, Grenville Province; *in* Summary of Field Work and Other Activities, 2014; Ontario Geological Survey, Open File Report 6300, p.16-1 to 16-12.

——— 2022. Field Trip 2 – Geology of the Grenville Front and the Grenville Front tectonic zone in the Sudbury area; *in* 68th Institute on Lake Superior Geology, Sudbury, Ontario, Proceedings, v.68, pt.2, p.103-146.

Easton, R.M. and James, R.S. 1997. Revisiting the disappearance of the Huronian in the Sudbury–Crerar area: insights from the geochemistry of amphibolites and paragneisses; abstract *in* 43rd Institute on Lake Superior Geology, Proceedings, v.43, pt.1, p.19-20.

Easton, R.M. and Murphy, E. 2002. Precambrian geology of Street Township, District of Sudbury; Ontario Geological Survey, Open File Report 6078, 149p.

Ercit, T.S. 1999. North versus south: NYF pegmatites in the Grenville Province of the Canadian Shield; The Canadian Mineralogist, v.37, p.818-819.

Grant, J.A., Pearson, W.J., Phemister, T.C. and Thomson, J.E. 1962. Broder, Dill, Neelon, and Dryden townships; Ontario Department of Mines, Geological Report 9, p.1-24.

Hewitt, D.F. 1963. Silica in Ontario; Ontario Department of Mines, Industrial Mineral Report 9, 36p.

James, R.S., Easton, R.M., Peck, D.C. and Hrominchuk, J.L. 2002. The East Bull Lake intrusive suite: Remnants of a ~2.48 Ga large igneous and metallogenic province in the Sudbury area of the Canadian Shield; Economic Geology, v.97, p.1577-1606.

Kamo, S.L. 2022. Report on U-Pb ID-TIMS geochronology for the Ontario Geological Survey: Bedrock Mapping Projects, Ontario, 2021-2022; internal U/Pb age report for the Ontario Geological Survey, Jack Satterly Geochronology Laboratory, Department of Geology, University of Toronto, Toronto, Ontario, 11p.

Krogh, T.E. 1989. Provenance and metamorphic ages in the Grenville (NW); *in* The Abitibi–Grenville Lithoprobe Project: 1989 Transect Report and Updated Proposal, Lithoprobe Abitibi–Grenville Project Workshop, March 1989, Lithoprobe Secretariat, University of British Columbia, Vancouver, British Columbia, Lithoprobe Report No.8, p.5-7.

Krogh, T.E. and Davis, G.L. 1970. Metamorphism 1700±100 m.y. and 800±100 m.y. ago in the northwest part of the Grenville Province of Ontario; Carnegie Institution of Washington, Yearbook 68, p.309-313.

Kwak, T.A.P. 1968. Metamorphic petrology and geochemistry across the Grenville Province–Southern Province boundary, Dill Township, Sudbury, Ontario; unpublished PhD thesis, McMaster University, Hamilton, Ontario, 200p.

——— 1971. Justification for both ionic and thermal reactions in Grenville Province pelitic rocks near Sudbury, Ontario; Canadian Journal of Earth Sciences, v.8, p.1333-1354.

Kyser, K. and Cuney, M. 2009. Geochemical characteristics of uranium and analytical methodologies; *in* Recent and not-so-recent developments in uranium deposits and implications for exploration; Mineralogical Association of Canada, Short Course Volume 39, p.23-55.

Lesher, C.M., Goodwin, A.M., Campbell, I.H. and Gorton, M.P. 1986. Trace-element geochemistry of ore associated and barren, felsic metavolcanic rocks in the Superior Province, Canada; Canadian Journal of Earth Sciences, v.23, p.222-237.

Lumbers, S.B. 1975. Geology of the Burwash area, districts of Nipissing, Parry Sound, and Sudbury; Ontario Division of Mines, Geological Report 116, 158p. Accompanied by Map 2271, scale 1:126 720.

Lyon, D. and Jobin-Bevans, S. 2001. Summary: High-silica occurrence, Secord property, prepared for Secord Silica Corporation; unpublished report, Sudbury Resident Geologist office, assessment file AFRO# 2.21492 AFRI# 41I07SW2004, 62p.

McAuley, J.B. 1996. An evaluation of potential high-purity silica sources: Preliminary site investigations, Volume 1; Ontario Geological Survey, Open File Report 5948, 481p.

Nesbitt, H.W. and Young, G.M. 1982. Early Proterozoic climates and plate motions inferred from major element chemistry of lutites; Nature, v.299, p.715-717.

Pattison, D.R.M., Chacko, T., Farquhar, J. and MacFarlane, C.R.M. 2003. Temperatures of granulite-facies metamorphism: Constraints from experimental phase equilibria and thermobarometry corrected for retrograde exchange; Journal of Petrology, v.44, p.867-900.

Pearson, W.J. 1959. Origin of the kyanite occurrences in the Wanapitei and Crocan Lake areas of Ontario; unpublished PhD thesis, Queen's University, Kingston, Ontario, 336p.

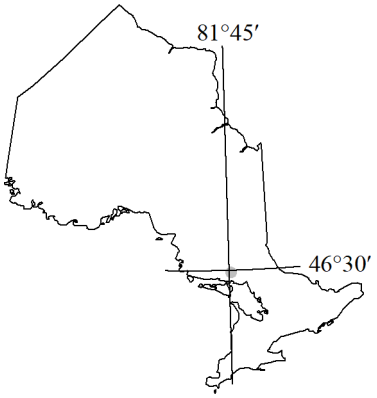
Prevec, S.A. 2004. Basement tracing using Mid-Proterozoic anorthosites straddling a palaeoterrane boundary, Ontario, Canada; Precambrian Research, v.129, p.164-184.

Sun, S-S. and McDonough, W F. 1989. Chemical and isotopic systematics of oceanic basalts: Implications for mantle compositions and processes; *in* Magmatism in ocean basins, Geological Society of London, Special Publication No.42, p.313-345.

Taylor, S.R. and McLennan, S.M. 1985. The continental crust: Its composition and evolution, Blackwell, Oxford, United Kingdom, 312p.

Vos, M.A., Smith, B.A. and Stevenato, R.J. 1981. Industrial minerals of the Sudbury area; Ontario Geological Survey, Open File Report 5329, 156p.

13. Project NE-22-001. Preliminary Geology of Hyman Township, Southern and Superior Provinces, Sudbury District, Northeastern Ontario



C.A. Gordon[1]

[1]Earth Resources and Geoscience Mapping Section, Ontario Geological Survey

INTRODUCTION

The geology of Hyman Township (Figure 13.1) represents a knowledge gap in recent Ontario Geological Survey (OGS) bedrock geology mapping between the southwest Sudbury area (Drury and Denison townships; Gordon, Simard and Généreux 2018; Gordon 2018) and Porter and Vernon townships (Easton 2006) (*see* Figure 13.1). To eliminate this gap, bedrock geology mapping of Hyman Township was initiated in 2022. The township was last mapped over 50 years ago (cf. Card 1965) before the establishment of the current Huronian Supergroup stratigraphy (*see* Robertson, Card and Frarey 1969) and was done with limited subdivision of the mafic intrusive rocks. The area is of interest for several reasons: 1) the area contains a past-producing uranium mine with reserves, a nickel-copper-platinum group element (PGE) prospect and numerous uranium and nickel-copper occurrences; 2) there is potential to identify new targets of economic interest such as Sudbury Igneous Complex–related offset dikes and breccia belts, East Bull Lake intrusive suite rocks and/or high-magnesium varieties of Nipissing gabbro; 3) potentially constrain the timing of deformation by using U/Pb geochronology to determine the age of mafic intrusions that crosscut regional deformation features; and; 4) characterization of mafic intrusive rocks currently of unknown affinity that have been characterized in adjacent townships.

The mapping project will focus on the following: a) defining the Huronian Supergroup stratigraphy; b) providing an improved subdivision of the mafic intrusive rocks; c) collecting new structural data; all of which can be used to better determine the macroscopic structural history of the township. This article summarizes results from the 2022 mapping program that focussed on the area north of Agnew Lake (Figure 13.2).

REGIONAL GEOLOGY

Hyman Township is located approximately 50 km west-southwest of Sudbury. It straddles the boundary between the Archean Superior Province and the Paleoproterozoic Southern Province (*see* Figure 13.1). In the township, Archean rocks are part of the Abitibi Subprovince and consist of the Birch Lake batholith (*circa* 2651 Ma: Kamo 2006; Easton and Heaman 2008) of the Ramsey–Algoma granitoid complex. The southern boundary of the Superior Province is overlain unconformably by supracrustal rocks of the Huronian Supergroup, which were deposited in a continental rift, and later on a continental platform, between 2450 and 2219 million years ago (Krogh, Davis and Corfu 1984; Bennett, Dressler and Robertson 1991). The Sudbury Igneous Complex (SIC), a remnant of an ancient meteorite crater that formed at 1850 Ma (Dietz 1964; Krogh, Davis and Corfu 1984), crops out approximately 4 km northeast

Summary of Field Work and Other Activities, 2022,
Ontario Geological Survey, Open File Report 6390, p.13-1 to 13-10.

© King's Printer for Ontario, 2022

and east of Hyman Township. The Sudbury Structure consists of a differentiated melt sheet, impact melt–bearing dikes (Offset dikes) and brecciated and shock metamorphosed footwall rocks (cf. Card et al. 1984).

The Sudbury area has been intruded by numerous mafic dikes and sills of various ages. These include the 1) Matachewan dike swarm (2480–2460 Ma: Heaman 1997; Bleeker et al. 2012), 2) East-Bull Lake intrusive suite (2480 Ma: Krogh, Davis and Corfu 1984; James et al. 2002), 3) Nipissing intrusive suite (2219–2210 Ma: Noble and Lightfoot 1992; Davey et al. 2019); 5) Trap dike swarm (1750 Ma: Bleeker et al. 2015); and 6) Sudbury dike swarm (1238 Ma: Krogh et al. 1987).

The area has been affected by several episodes of deformation and metamorphism. Regional metamorphic grade ranges from subgreenschist to amphibolite facies (Card 1978b). Early ductile deformation of Huronian Supergroup strata has historically been interpreted to have started prior to, or concurrent with, emplacement of the Nipissing intrusive suite, with regional folding continuing after the emplacement of the Nipissing sills (cf. Card 1978a; Card et al. 1984; Easton 2006). Subsequent northwest-directed compression produced a fold-and-thrust belt along the Superior craton margin, as well as south-dipping reverse shear zones (Card et al. 1984). Recent studies have attributed most of the deformation in the Sudbury area to the Yavapai and Mazatzal orogenies (*circa* 1760 to 1650 Ma; Papapavlou et al. 2017, and references therein). The lower age limit of deformation is constrained by the age of the undeformed Sudbury dike swarm (1238±4 Ma) (Krogh et al. 1987).

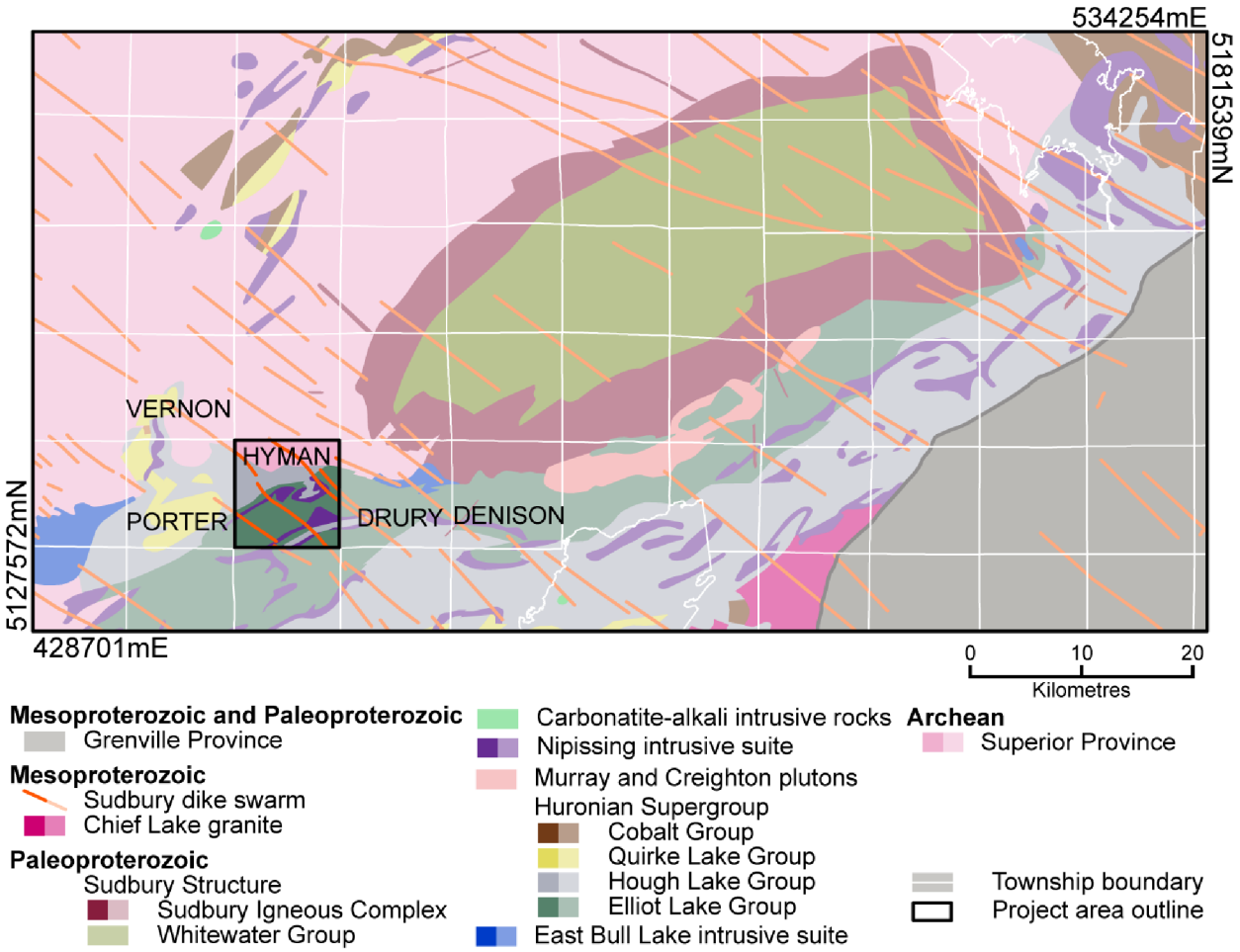


Figure 13.1. Simplified geological map of the Sudbury area. Geology *modified from* Ontario Geological Survey (2011). Note, darker colours indicate geological units in Hyman Township, which is outlined in black. Universal Transverse Mercator (UTM) co-ordinates provided using North American Datum 1983 (NAD83) in Zone 17.

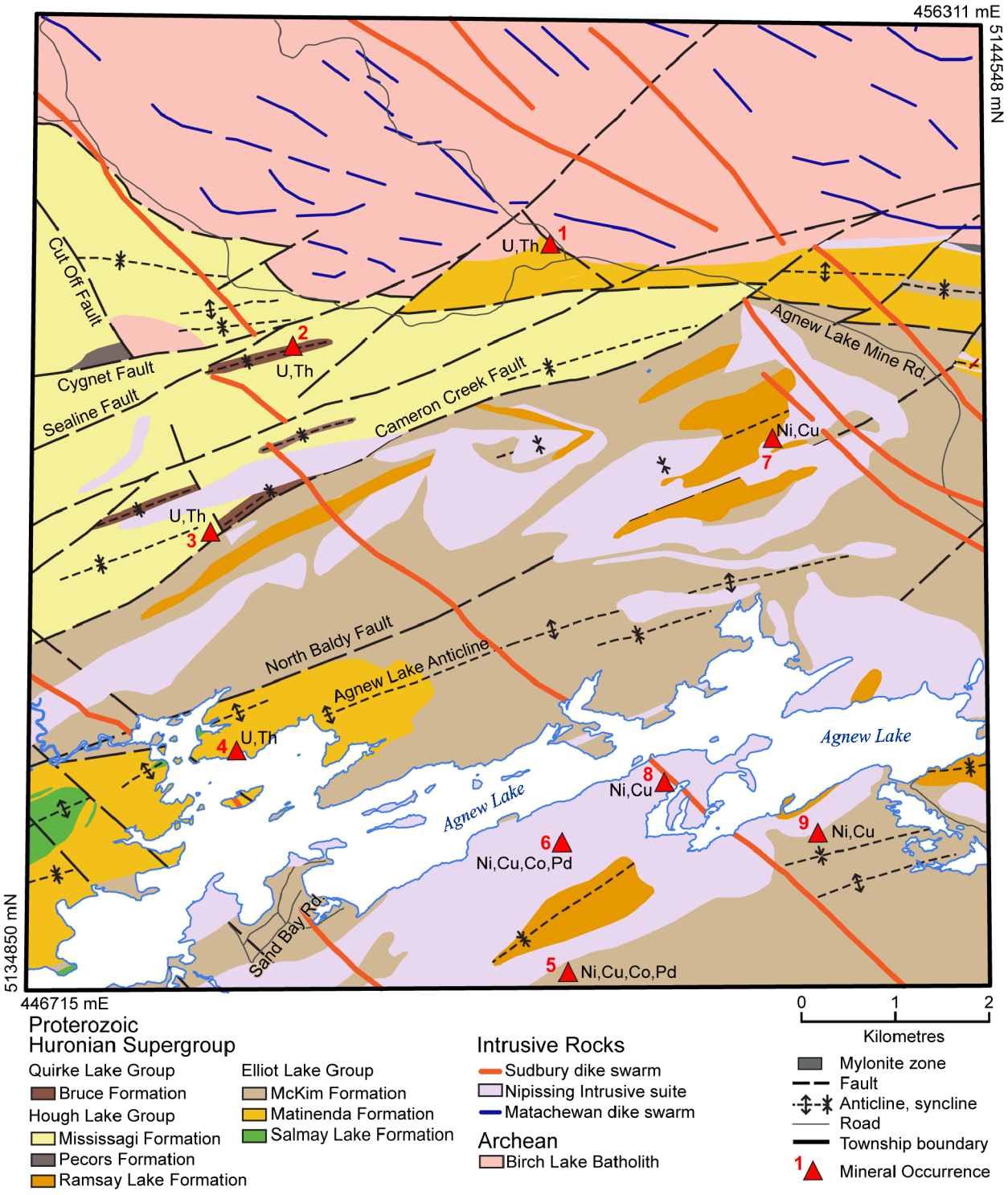


Figure 13.2. Simplified geological map of Hyman Township, based on mapping in 2022 and *modified from* Card (1965). Mineral occurrences are listed in Table 13.1. All UTM co-ordinates are provided using NAD83 in Zone 17.

GEOLOGICAL OVERVIEW

Figure 13.2 presents the preliminary results of mapping in Hyman Township. Regional metamorphism of the area is typically greenschist facies, with amphibolite-facies rocks locally observed in the southwest. For the sake of clarity, the prefix "meta" has been omitted for the rock names hereafter in the article (e.g., gabbro versus metagabbro).

Birch Lake Batholith and Matachewan Dike Swarm

The northern quarter of Hyman Township is underlain by granite of the Archean Birch Lake batholith. Two phases were observed: 1) porphyritic granite and 2) medium-grained, equigranular granite and quartz monzonite. The Birch Lake batholith is intruded by numerous fine- to medium-grained, northwest-trending mafic dikes. These dikes appear to be restricted to the Archean basement. Pending further geochemical investigation, the northwest-trending intrusions have all been classified as Matachewan swarm dikes.

Granitic rocks crop out within the area of the Mississagi Formation south of the Birch Lake batholith–Mississagi Formation unconformity. These granitoid outliers have historically been interpreted as Archean basement within the folded Huronian Supergroup. However, granite plutons of Mesoproterozoic age (i.e., the Chief Lake granite) are known outside of the map area. Pending geochronological results, these outliers are tentatively assigned to the Birch Lake batholith.

Huronian Supergroup

The Huronian Supergroup consists of 4 groups; from lowermost to uppermost, these are the Elliot Lake, Hough Lake, Quirke Lake and Cobalt groups (Bennett, Dressler and Robertson 1991, and references therein). Units from the Elliot Lake, Hough Lake and lowermost Quirke Lake groups occur in Hyman Township. Most of the Huronian Supergroup strata are subvertical and are generally northeast trending. Reversals of facing direction and/or repetition of stratigraphy define the synclines and anticlines shown in Figure 13.2.

ELLIOT LAKE GROUP

Volcanic rocks, known as the Salmay Lake Formation, crop out in the southwestern portion of Hyman Township in the core of the Agnew Lake anticline (*see* Figure 13.2) The Salmay Lake Formation is composed predominantly of mafic flows interbedded with minor amounts of felsic lapilli tuff. A polymictic conglomerate with abundant volcanic and gabbro clasts (Photo 13.1A), present in the upper part of the formation, is tentatively assigned to the Salmay Lake Formation. Rocks of the Salmay Lake Formation are metamorphosed to at least lower amphibolite facies and commonly contain garnet porphyroblasts (Photo 13.1B). The contact with sedimentary rocks of the overlying Matinenda Formation is transitional.

The Matinenda Formation crops out in the southwestern portion of Hyman Township, where it is folded along with the Salmay Lake and McKim formations, and in the northern half of Hyman Township where it is bounded to the north by the Birch Lake batholith and to the south by the overlying McKim and Mississagi formations. The Matinenda Formation consists of quartz and feldspathic arenites with local interbedded siltstone and conglomerate beds. The contact with the overlying McKim Formation was not observed, but is known to be transitional in adjacent townships to the east (Gordon, Simard and Généreux 2018). The contact between the Matinenda and Mississagi formations is interpreted to be faulted.

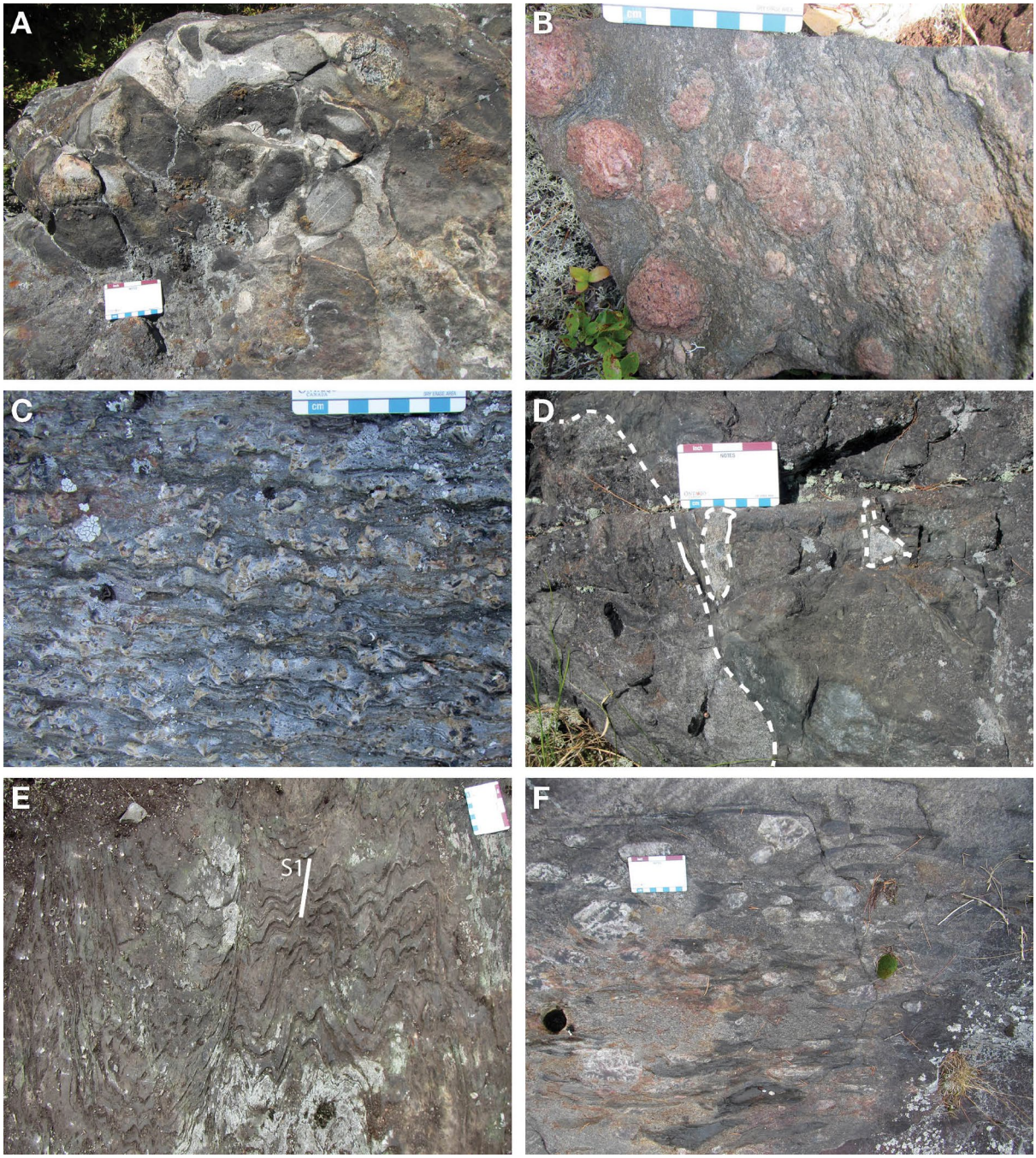


Photo 13.1. A) Polymictic conglomerate, Salmay Lake Formation, Elliot Lake Group. Rounded clasts of basalt, gabbro and arenite are enclosed in a light-grey, garnet-bearing matrix (UTM 447367E 5136655N). **B)** Garnet amphibolite, Salmay Lake Formation, Elliot Lake Group. Garnet porphyroblasts, up to 3 cm in diameter, are enclosed in a moderately foliated amphibolite groundmass (UTM 446890E 5136225N). **C)** Moderately foliated staurolite-garnet-biotite schist, McKim Formation, Elliot Lake Group. Staurolite porphyroblasts are up to 2 cm in diameter and weather high. Garnet and biotite range from 1 to 3 mm in diameter. Sedimentary bedding is preserved and visible as thick laminations (UTM 449669E 5136701N). **D)** Contact between the mesocratic gabbro (left) and melagabbro (right) phases of a Nipissing sill. Clasts of mesocratic gabbro are present in the melagabbro (UTM 453549E 5140396N). **E)** M-folds and axial planar foliation (S_1) in mudstone of the McKim Formation, Elliot Lake Group, in the hinge of the Agnew Lake anticline. The axial planar foliation is parallel to the regional foliation and trends northeast (UTM 454596E 5141569N). **F)** Uraniferous oligomictic quartz pebble conglomerate bed in feldspathic arenite, Matinenda Formation, Elliot Lake Group. Subrounded to angular clasts of quartz and basalt in a coarse-grained, quartz-rich, sulphide-bearing matrix. The conglomerate bed is up to 1 m thick (UTM 448212E 5137405N). Scale card in all images is 9 cm wide. All UTM co-ordinates are provided using NAD83 in Zone 17.

The McKim Formation is the most aerially extensive Huronian Supergroup unit in Hyman Township with its preserved sequence being thickened by folding. It consists of mudstone, siltstone and schistose equivalents. Lower greenschist-facies assemblages in the northeast of Hyman Township are characterized by staurolite-bearing siltstone-mudstone. Amphibolite-facies metamorphism in the southwestern portion of Hyman Township is characterized by staurolite-garnet-biotite schist (Photo 13.1C).

HOUGH LAKE AND QUIRKE LAKE GROUPS

The Ramsay Lake Formation is the lowermost formation of the Hough Lake Group. In Hyman Township, it is a bilithic conglomeratic subfeldspathic arenite similar to what Gordon, Simard and Généreux (2018) referred to as the "beige" member in Drury Township. In Hyman Township, the Ramsay Lake Formation is present south of the Cameron Creek fault. The preserved sequence is folded with, and wedged between, large mafic sills and mudstone and siltstone of the McKim Formation.

The Mississagi Formation (Hough Lake Group) crops out in northwestern Hyman Township and is bounded to the north either by the Archean basement or the Matinenda Formation and to the south by the Cameron Creek fault. The Mississagi Formation consists of quartz arenite with local siltstone beds. Thin, discontinuous slivers of siltstone and mudstone, and bilithic matrix-supported conglomerate crop out along folds within the Mississagi Formation. These slivers of siltstone-mudstone and conglomerate are tentatively assigned to the Pecors Formation (Hough Lake Group) and the Bruce Formation (Quirke Lake Group), respectively.

Nipissing Intrusive Suite, Sudbury Dike Swarm and Mafic Intrusions of Unknown Affinity

Both large and small, approximately northeast-trending, Nipissing sills have intruded and are folded along with their host Huronian Supergroup rocks. The larger Nipissing sills typically occur at, or near, the contact between the Ramsay Lake and McKim formations. Two phases were observed in the larger intrusions: 1) mesocratic gabbro and 2) melagabbro to amphibolite. Locally, melagabbro is observed to intrude the gabbro phase (Photo 13.1D). Northwest-trending olivine diabase dikes of the Sudbury dike swarm crosscut the Huronian Supergroup, Nipissing sills and Archean basement rocks. The Sudbury swarm dikes are undeformed and postdate metamorphism. Narrow, northeast- and east-trending mafic dikes intruded the Huronian Supergroup and, to a lesser extent, the Archean basement. These intrusions are likely representative of the Trap dike swarm (*circa* 1750 Ma). They are not visible in the regional aeromagnetic data and are difficult to trace between exposures. Additional petrographic and geochemical work on these dikes is required before classification. These intrusions are not shown on Figure 13.2.

Sudbury Breccia

Sudbury Breccia is a pseudotachylite thought to have formed during the cratering phase of the Sudbury impact event (cf. Card et al. 1984). In Hyman Township, narrow, discontinuous breccia veins have intruded rocks of the Huronian Supergroup and the Birch Lake batholith. The breccia veins are matrix supported and contain clasts of the host rock. The matrix is fine grained and dark grey to green.

Structural Geology

The rocks in Hyman Township exhibit a complex history of folding and faulting. A brief summary follows.

FOLDING AND REGIONAL FOLIATION

Kilometre-scale, northeast-trending folds are present and are related to the regional northeast- and east-trending folds in the Southern Province fold belt (cf. Card 1978a). These folds strongly control the present structural configuration of Huronian Supergroup strata in Hyman Township. The folds are consistent with the pervasive northeast-trending subvertical foliation observed in most rocks in the township (Photo 13.1E). Adjacent to the Huronian Supergroup–Birch Lake batholith contact, smaller scale folds are oriented parallel to the contact. Away from the contact, smaller scale folds parallel the regional northeast trend. The Nipissing sills are folded along with the Huronian Supergroup strata, consistent with earlier interpretations that much of the regional folding postdates Nipissing magmatism (Noble and Lightfoot 1992; Corfu and Andrews 1986; Card 1978a; Bennett, Dressler and Robertson 1991; Easton 2006).

FAULTING

To date, 4 faulting events have been recognized. In the northern half of Hyman Township, bedding-parallel faults at the base of the Matinenda Formation correlate with the bedding-parallel thrust faults recognized in Drury Township (Gordon, Simard and Généreux 2018). These thrust faults are folded along with Huronian Supergroup strata and, therefore, are interpretated to predate regional folding. The Creighton–Victoria deformation zone, a west-northwest- to east-trending mylonite zone, present along the contact of the Huronian Supergroup and Archean granitoid basement in Drury Township (Gordon, Simard and Généreux 2018), extends into the easternmost part of Hyman Township. Its extent is limited compared to Drury Township. The timing of the Creighton–Victoria deformation zone is interpreted to be coeval with regional folding (Généreux et al. 2018). Throughout Hyman Township, numerous northeast-trending faults exhibit significant control on, and have disrupted, the Huronian Supergroup stratigraphy and Nipissing sills. These include the Cameron Creek, North Baldy, Sealine and Cygnet faults (*see* Figure 13.2). The northeast-trending faults are part of the South Range shear zone defined in the Sudbury area by Shanks and Schwerdtner (1991). In the western half of Hyman Township, another set of late faults truncate folded Huronian Supergroup strata. These faults are northwest trending and include the Cut Off fault (*see* Figure 13.2).

MINOR STRUCTURES

Shear zones and regional foliation are overprinted by a later event (or events) that is manifested in localized north-northwest-trending crenulations, kink bands and small-scale, north-trending folds. These structures are observed throughout the township.

ECONOMIC GEOLOGY

Hyman Township contains a past-producing uranium mine with reserves (Agnew Lake Mine), a nickel-copper-PGE prospect (Kordol South showing) and numerous uranium and nickel-copper occurrences. A summary of mineral occurrences in Hyman Township is presented in Table 13.1. Uranium-rich horizons are associated with conglomeratic units of the Matinenda Formation and are of similar character to the deposits in the Elliot Lake–Blind River area (cf. Robertson 1976). The uranium occurrences are present adjacent to Huronian Supergroup–Birch Lake batholith contact or occur in the core of the Agnew Lake anticline (*see* Figure 13.2). The uranium-bearing lenses themselves are discontinuous and narrow (Photo 13.1F). Intervening arenite beds are frequently thorium rich. Two historic uranium and thorium occurrences occur in an area currently interpreted to be underlain by rocks of the Bruce and Mississagi formations. The location and host unit of these occurrences has not yet been verified by the author.

Table 13.1. Ontario Mineral Inventory (OMI) occurrences in Denison Township (Ontario Geological Survey 2022).

Location Number (shown on Figure 13.2)	Mineral Deposit Category	Deposit Name	Commodity	Host Rock	OMI Number
1	Past-producing mine with reserves	Agnew Lake Mine	U, Th	Quartz-pebble conglomerate	MDI41I05NE00009
2	Occurrence	Richore occurrence	U, Th	Quartz-pebble conglomerate, granite	MDI41I05NE00038
3	Occurrence	East Bay Gold DDH EB-3, Rose showing	U, Th	Quartz-pebble conglomerate	MDI41I05NE00039
4	Occurrence	Ridge showing	U, Th	Quartz-pebble conglomerate	MDI41I05NE00041
5	Prospect	Kordol South showing	Ni, Cu, Co, Pd	Gabbro	MDI41I05SE00069
6	Occurrence	Kordol North showing	Ni, Cu, Co, Pd	Gabbronorite	MDI41I05NE00058
7	Occurrence	Pond showing	Ni, Cu	Sheared gabbro and quartz veins	MDI41I05NE00043
8	Discretionary occurrence	Kordol No.3 zone	Ni, Cu	Altered gabbro	MDI41I05NE00057
9	Discretionary occurrence	Kordol No.4 zone	Ni, Cu	Altered gabbro	MDI41I05NE00056

Abbreviations: *Co, cobalt; Cu, copper; DDH, diamond-drill hole; MDI, Mineral Deposit Inventory; Ni, nickel; OMI, Ontario Mineral Inventory; Pd, palladium; Th, thorium; U, uranium.*

Localized lenses of sulphide mineralization containing nickel and copper (±PGE) have been identified in the larger gabbroic sills of the Nipissing intrusive suite and in shear zones that crosscut the gabbroic sills. Mineralization consists of disseminated to locally massive pyrrhotite, chalcopyrite and pyrite.

ACKNOWLEDGMENTS

The author would like to thank J. Courchesne and B. Gaudet for their assistance during the 2022 field season. R.M. Easton and M. Duguet (OGS) are thanked for their ongoing guidance and assistance on this project; and J.E. Chartrand, K.H. Yeung, S.A. Evers and P. Gervais, for all the assistance with databases, software logistics, sample preparation and drafting. Special thanks are extended to Atikameksheng Anishnawbek First Nation, Sagamok First Nation and Whitefish River First Nation for allowing the Ontario Geological Survey to map their traditional land use area. Thanks are also extended to Vale Canada Limited, Magna Mining Inc. and Skead Holdings Ltd. for providing access to properties, and for all support that has been provided.

REFERENCES

Bennett, G.B., Dressler, B.O. and Robertson, J.A. 1991. The Huronian Supergroup and associated intrusive rocks; Chapter 14 *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, p.549-591.

Bleeker, W., Hamilton, M.A., Ernst, R.E. and Söderlund, U. 2012. Resolving the age structure of the Matachewan event: Magmatic pulses at ca. 2445–2452 Ma, 2458–2461 Ma, and 2475–2480 Ma; unpublished CAMIRO Reports A96, A97 and A98, 17p.

Bleeker, W., Kamo, S.L., Ames, D.E. and Davis, D. 2015. New field observations and U-Pb ages in the Sudbury area: Toward a detailed cross-section through the deformed Sudbury Structure; *in* Targeted Geoscience Initiative 4: Canadian Nickel-Copper-Platinum Group Elements-Chromium Ore Systems – Fertility, Pathfinders, New and Revised Models, Geological Survey of Canada, Open File 7856, p.151-156.

Dietz, R.S. 1964. Sudbury Structure as an astrobleme; Journal of Geology, v.72, p.412-434.

Card, K.D. 1965. Geology of Hyman and Drury townships, District of Sudbury; Ontario Department of Mines, Geological Report 34, 38p.

——— 1978a. Geology of the Sudbury–Manitoulin area; Ontario Department of Mines, Report 166, 238p.

——— 1978b. Metamorphism of the Middle Precambrian (Aphebian) rocks of the eastern Southern Province; *in* Metamorphism in the Canadian Shield; Geological Survey of Canada, Paper 78-10, p.269-282.

Card, K.D., Gupta, V.K., McGrath, P.H. and Grant, F.S. 1984. The Sudbury Structure: Its regional geological and geophysical setting; *in* The geology and ore deposits of the Sudbury Structure, Ontario Geological Survey, Special Volume 1, p.25-43.

Corfu, F. and Andrews, A.J. 1986. A U–Pb age for mineralized Nipissing diabase, Gowganda; Canadian Journal of Earth Sciences, v.23, p.107-109.

Davey, S., Bleeker, W., Kamo, S[.L.], Davis, D.[W], Easton, [R.]M. and Sutcliffe, R.H. 2019. Ni-Cu-PGE potential of the Nipissing sills as part of the ca. 2.2 Ga Ungava large igneous province; *in* Targeted Geoscience Initiative: 2018 report of activities; Geological Survey of Canada, Open File 8549, p.403-419.

Easton, R.M. 2006. Precambrian geology, Porter and Vernon townships; Ontario Geological Survey, Preliminary Map P.2845, scale 1:20 000.

Easton, R.M. and Heaman, L.M. 2008. Detrital zircon geochronology of Huronian Supergroup sandstones located within the Vernon structure, north of Espanola, Ontario; abstract *in* 54th Institute on Lake Superior Geology, Proceedings, v.54, pt.1, p.21-22.

Généreux, C-A., Lafrance, B., Tinkham, D.K. and Gordon, C.A. 2018. Polyphase deformation in the southwest Sudbury impact structure; oral presentation, Resources for Future Generations 2018 conference, International Union of Geological Sciences, Canadian Federation of Earth Sciences, Canadian Institute of Mining, Metallurgy and Petroleum, Geological Association of Canada and Mineralogical Association of Canada, Vancouver, British Columbia, June 16–21, 2018.

Gordon, C.A. 2018. Precambrian geology of Denison Township, southwest Sudbury Structure; *in* Summary of Field Work and Other Activities, 2018, Ontario Geological Survey, Open File Report 6350, p.13-11 to 13-10.

Gordon, C.A., Simard, R-L. and Généreux, C-A. 2018. Precambrian geology of Drury Township, southwest Sudbury Structure: Explanatory notes for Preliminary Map P.3823; Ontario Geological Survey, Open File Report 6346, 49p.

Heaman, L.M. 1997. Global mafic magmatism at 2.45 Ga: Remnants of an ancient large igneous province?; Geology, v.25, p.299-302.

James, R.S., Easton, R.M., Peck, D.C. and Hrominchuk, J.L. 2002. The East Bull Lake intrusive suite: Remnants of a ~2.48 Ga large igneous and metallogenic province in the Sudbury area of the Canadian Shield; Economic Geology, v.97, p.1577-1606.

Kamo, S.L. 2006. Report on U-Pb geochronological data from the southern Abitibi Subprovince, Bannockburn–Montrose and Vernon townships, and the Grenville Front region, Thistle–Sisk townships, Ontario; internal U/Pb age report prepared for the Ontario Geological Survey, Jack Satterly Geochronology Laboratory, Department of Geology, University of Toronto, Toronto, Ontario, 20p.

Krogh, T.E., Corfu, F., Davis, D.W., Dunning, G.R., Heaman, L.M., Kamo, S.L., Machado, N., Greenough, J.D. and Nakamura, E. 1987. Precise U-Pb isotope ages of diabase dikes and mafic to ultramafic rocks using trace amounts of baddeleyite and zircon; *in* Mafic dike swarms, Geological Association of Canada, Special Paper 34, p.147-152.

Krogh, T.E., Davis, D.W. and Corfu, F. 1984. Precise U-Pb zircon and baddeleyite ages for the Sudbury area; *in* The geology and ore deposits of the Sudbury Structure; Ontario Geological Survey, Special Volume 1, p.431-446.

Noble, S.R. and Lightfoot, P.C. 1992. U–Pb baddeleyite ages for the Kerns and Triangle Mountain intrusions, Nipissing diabase, Ontario; Canadian Journal of Earth Sciences, v.29, p.1124-1129.

Ontario Geological Survey 2011. 1:250 000 scale bedrock geology of Ontario; Ontario Geological Survey, Miscellaneous Release—Data 126 – Revision 1.

——— 2022. Ontario Mineral Inventory; Ontario Geological Survey, Ontario Mineral Inventory (April 2022 update).

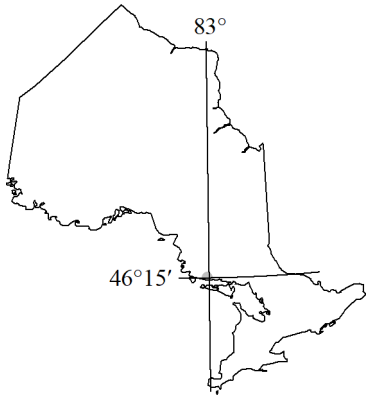
Papapavlou, K., Darling, J.R., Storey, C.D., Lightfoot, P.C., Moser, D.E. and Lasalle, S. 2017. Dating shear zones with plastically deformed titanite: New insights into the orogenic evolution of the Sudbury impact structure (Ontario, Canada); Precambrian Research, v.291, p.220-235.

Robertson, J.A. 1976. The Blind River uranium deposits: The ores and their setting; Ontario Division of Mines, Report 147, 73p.

Robertson, J.A., Card, K.D. and Frarey, M.J. 1969. The federal–provincial committee on Huronian stratigraphy progress report; Ontario Department of Mines, Miscellaneous Paper 31, 26p.

Shanks, W.S. and Schwerdtner, W.M. 1991. Structural analysis of the central and southwestern Sudbury Structure, Southern Province, Canadian Shield; Canadian Journal of Earth Sciences, v.28, p.411-430.

14. Project SO-19-001. Preliminary Geology of Patton and Thompson Townships, Iron Bridge Area, Southern Province, Northeastern Ontario



E.C.G. Hastie[1], P.J. MacDonald[1] and M. Duguet[1]

[1]Earth Resources and Geoscience Mapping Section, Ontario Geological Survey

INTRODUCTION

The great oxidation event and oxyatmoversion are terms used to describe the rise of oxygen in the Earth's atmosphere during the Paleoproterozoic Era (Roscoe 1973; Holland 2006; Lyons, Reinhard and Planavsky 2014). The rocks of the Huronian Supergroup (2450–2219 Ma) that were deposited during this time in what is now Ontario, record important evidence for these processes as well as Earth's earliest glacial periods (Hoffman and Schrag 2002; Rasmussen, Bekker and Fletcher 2013). Limited research on the Huronian Supergroup and the gabbroic rocks of the Nipissing intrusive suite has occurred west of Sudbury between Blind River and Iron Bridge (Figure 14.1) even though this area contains numerous well-exposed outcrops that provide information critical to understanding Earth's early history.

Initiated in 2019 (Hastie and Vice 2019), this multi-year project will update the bedrock geology maps for Scarfe, Cobden, Patton and Thompson townships at 1:20 000 scale; the 2022 field season focussed on the latter 2 townships (*see* Figure 14.1). Stratigraphic units from the Matinenda to Lorrain formations of the Huronian Supergroup, along with gabbroic sills and dikes of the Nipissing intrusive suite, occur in the area along the shallowly dipping southern limb of the Chiblow Lake anticline and represent a near-complete cross section of the Huronian Supergroup. Previous mapping at larger scales that occurred between 1953 and 1960 (Robertson 1963, 1964) requires revision in both detail and stratigraphic nomenclature. Thus, the broad objectives of the project are to provide updated bedrock geology and revised stratigraphic subdivisions, where necessary, by using modern geochronological, geochemical and petrological data. In addition, the project will investigate the aggregate and economic mineral potential in the area. This project is being conducted in partnership with Mississauga First Nation and much of the project area is within their traditional and reserve lands.

GEOLOGICAL SETTING

The southern limb of the Chiblow Lake anticline is composed of gently dipping metasedimentary rocks of the Huronian Supergroup that are underlain by Archean granitoid rocks (Bennett, Dressler and Robertson 1991) along the shoreline of Lake Huron, and that are cut by the gabbroic rocks of the Nipissing intrusive suite (*see* Figure 14.1). The deposition of the Huronian Supergroup occurred between *circa* 2450 and 2219 Ma, the emplacement ages of the basal volcanic rocks and the Nipissing intrusive suite (Krogh, Davis and Corfu 1984; Corfu and Andrews 1986; Ketchum et al. 2013; Davey et al. 2019).

Summary of Field Work and Other Activities, 2022,
Ontario Geological Survey, Open File Report 6390, p.14-1 to 14-7.

© King's Printer for Ontario, 2022

The bedrock in Patton and Thompson townships has been previously interpreted to consist predominantly of rocks of the Gowganda Formation and some Neoarchean basement rocks along the shore of Lake Huron that were both cut by Nipissing intrusive suite gabbroic rocks. Generally, the metasedimentary rocks have been metamorphosed to lower greenschist facies, but, along the synsedimentary Murray Fault (Zolnai, Price and Helmstaedt 1984) in southern Thompson and Cobden townships (*see* Figure 14.1), it is likely that some areas were metamorphosed to amphibolite facies (Card 1978).

GEOLOGY OF PATTON AND THOMPSON TOWNSHIPS

Archean Granitoid Rocks

The southern portion of Thompson Township along the north shore of Lake Huron (*see* Figure 14.1) is host to Archean granitoid rocks, the age of which is *circa* 2660 Ma (Sutcliffe 2020). This age is consistent with that of the Ramsey–Algoma granitoid complex (Card 1979; Petrus et al. 2016). These

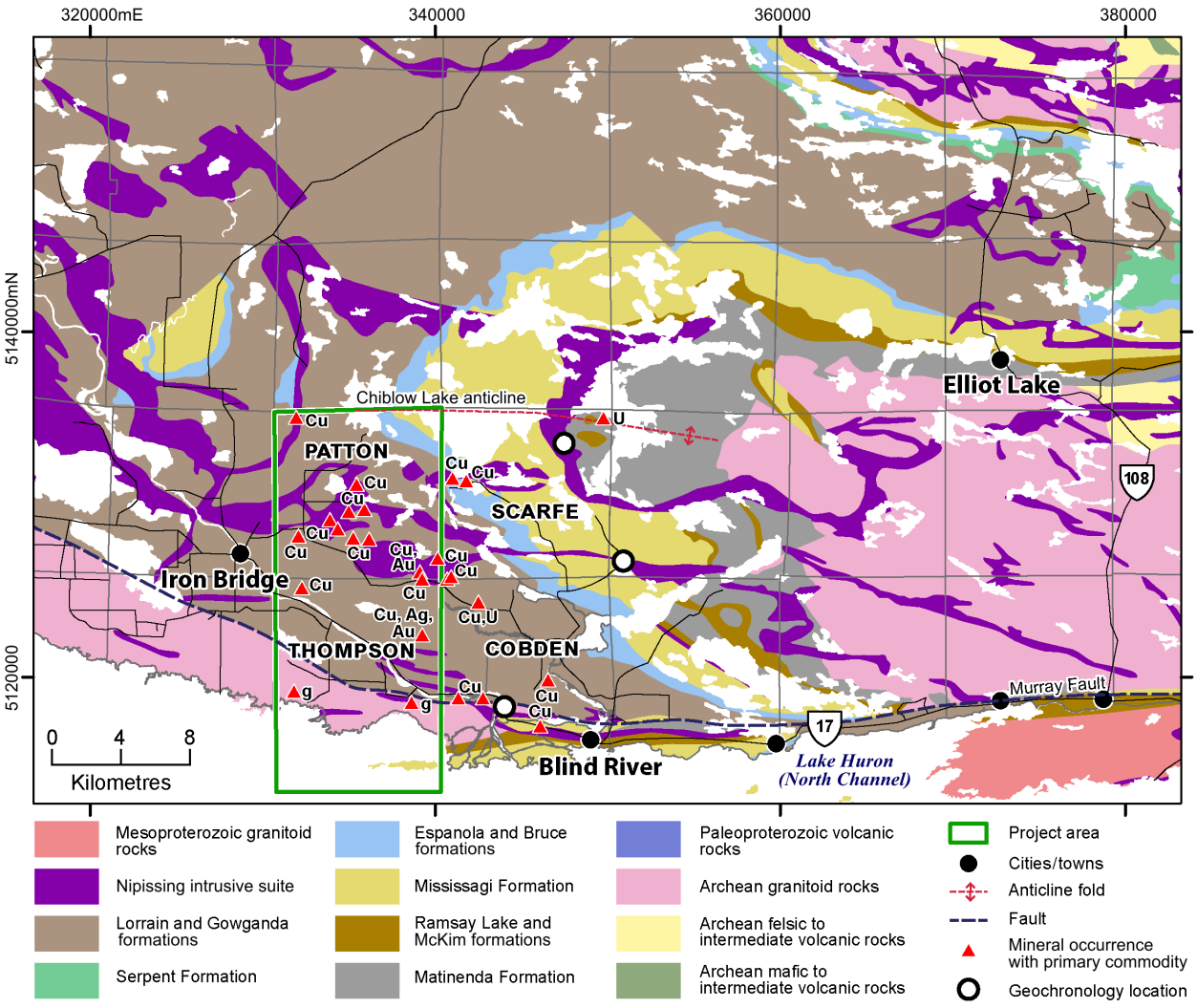


Figure 14.1. Simplified bedrock geology map of Scarfe and Cobden townships and surrounding area (*modified from* Ontario Geological Survey 2011). Note for clarity, mineral occurrences are shown only in Scarfe, Cobden, Thompson and Patton townships (Ontario Mineral Inventory; Ontario Geological Survey 2022). Abbreviations: Ag, silver; Au, gold; Cu, copper; g, granite; U, uranium. Universal Transverse Mercator (UTM) co-ordinates provided using North American Datum (NAD83) in Zone 17.

granitoid rocks are strongly hematized and are typically medium to coarse grained with a granitic to granodioritic composition (Photo 14.1A). The unconformity between these granitoids and the Huronian Supergroup was not observed in Thompson Township because it is obscured by the Murray Fault and related topographic features (*see* Figure 14.1). To fully ascertain the nature of this contact, it is likely that diamond-drill core would need to be investigated.

Mississagi Formation (Hough Lake Group)

The Mississagi Formation crops out in the northeast portion of Patton Township on the southern shore of Chiblow Lake (*see* Figure 14.1). It consists of medium- to coarse-grained grey sandstones that display local crossbedding. Any contact with the underlying Pecors Formation was not observed and has yet to be identified in work from this mapping season or that done in 2019 (Hastie and Vice 2019).

Bruce Formation (Quirke Lake Group)

The Bruce Formation also crops out in the northeast portion of Patton Township where it unconformably overlies the Mississagi Formation sandstones (*see* Figure 14.1). The formation consists of matrix-supported conglomerates with granitoid and quartzite clasts and a dark grey to black sandy matrix that commonly contains 0.1 to 1 cm quartz grains and millimetre-scale biotite grains (Hastie and Vice 2019).

Espanola Formation (Quirke Lake Group)

The Espanola Formation consists of chemical metasedimentary rocks that in Patton Township is typically a limestone that can range from thinly bedded, to beds up to 50 cm thick (Photo 14.1B). It can be found in northwest Patton Township and was also previously interpreted to crop out along the southern shore of Chiblow Lake (*see* Figure 14.1; Robertson 1963), but, until now, had not been found or sampled along the Chiblow Lake shoreline. Confirmation of the location of the Espanola Formation is an important marker horizon to distinguish conglomerates of the lower Coleman Member of the Gowganda Formation from the Bruce Formation given that there is no evidence for the Serpent Formation in the project area and that these conglomerates can locally resemble one another.

Gowganda Formation (Cobalt Group)

The Gowganda Formation is a dominant rock unit in the project area, especially in Thompson Township (*see* Figure 14.1) where it can be subdivided into the Coleman and Firstbrook members (Rainbird and Donaldson 1988; Junnila and Young 1995).

COLEMAN MEMBER

In Thompson Township, the Coleman Member is typically a matrix- to clast-supported conglomerate (Photo 14.1C) with clasts ranging in size from 1 to 100 cm that are dominantly granitoid in composition. It appears to have relatively sharp contacts with the Firstbrook Member siltstones stratigraphically above, but some tiny granitoid clasts (<1 cm) can be found in the lowermost part of these Firstbrook Member beds.

FIRSTBROOK MEMBER

This unit is a thinly laminated to thinly bedded, with high magnetic susceptibility (10 to 550 $\times 10^{-3}$ SI units). It has alternating beds of red to purple siltstone and brown to grey mudstone and some local signs of soft sediment deformation (Photo 14.1D). The reappearance of the Coleman Member and/or repetitive

sequences of conglomerates and siltstones toward the southwest part of the project area appears to be strictly controlled by subhorizontal bedding and/or topographic changes rather than reflecting any actual stratigraphic or facies changes.

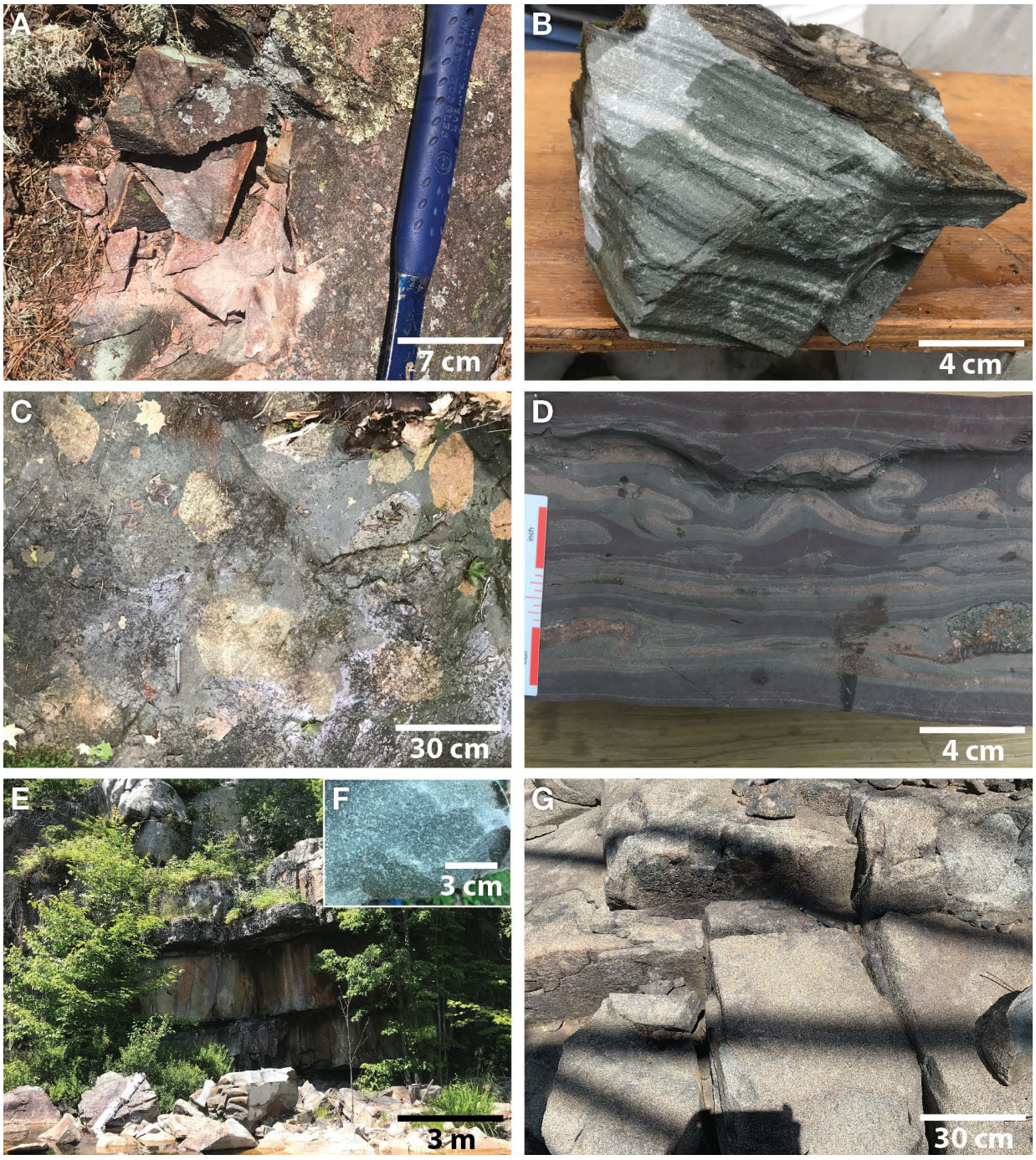


Photo 14.1. Representative photos of geological features in the map area. **A)** Strongly hematized Archean granitoid (UTM 331337E 5119128N). **B)** Thinly interbedded limestone of the Espanola Formation (UTM 336853E 5134578N). **C)** Matrix- to clast-supported conglomerate of the Gowganda Formation (UTM 332745E 5135216N). **D)** Rhythmically bedded, red to purple siltstone and brown to grey mudstone of the Gowganda Formation (UTM 339185E 5122221N). **E)** Shoreline outcrop of the Lorrain Formation (UTM 337972E 5132313N). **F)** Fine- to medium-grained quartz arenite of the Lorrain Formation (UTM 336228E 5131710N). **G)** Coarse-grained mesocratic gabbro of the Nipissing intrusive suite (UTM 338184E 5127410N). All UTM co-ordinates provided using NAD83 in Zone 17.

Lorrain Formation (Cobalt Group)

Although previous maps indicated that much of Patton Township consisted of the Gowganda Formation, mapping in 2022, along with descriptions from previous reports and close examination of the maps of Robertson (1963), indicate that a large portion (i.e., >30%) of Patton Township consists of the Lorrain Formation. These rocks have excellent exposure on the shoreline of Darrell Lake (Photo 14.1E). The most common unit is a white to grey fine- to medium-grained quartz arenite (Photo 14.1F) with beds that range from 1 to 3 m in thickness (*see* Photo 14.1E). Locally along the shore of Darrell Lake, where the arkose content of the rock increases slightly, pebble conglomerate beds can also be found in the Lorrain Formation.

Nipissing Intrusive Suite

Large areas of Patton Township and the southern portion of Thompson Township contain sills and dikes of fine- to coarse-grained mesocratic to melanocratic gabbro (*see* Figure 14.1; Photo 14.1G). Two samples selected in 2019 for geochronology (*see* Figure 14.1) returned U/Pb zircon ages of 2214±2 Ma (folded sill) and 2212±1.5 Ma (axial planar dike) (Kamo 2020). Although the coeval nature of these ages may suggest that the deformation that formed the Chiblow Lake anticline and, by extension, the Quirke Lake syncline, took place between 2212 and 2214 Ma, the folding of rock units that define the Chiblow Lake anticline is gentle. Consequently, further confirmation of the timing of deformation will require obtaining ages on dikes that crosscut both limbs of the fold.

RESOURCE POTENTIAL

The Nipissing intrusive suite along the north shore of Lake Huron has been investigated previously for aggregate potential (Ontario Geological Survey and Golder Associates Ltd. 1996) and an operating quarry approximately 65 km to the west in Bruce Mines (Ontario Trap Rock Ltd.) also highlights the potential for similar aggregate resources in the Blind River and Iron Bridge areas. Future work as part of this project will test appropriate sites of Nipissing intrusive suite rocks to establish a baseline of data that can be used to initially assess the aggregate potential of these rocks.

Historic copper occurrences can be found throughout the area (*see* Figure 14.1) (Pearson, Bretzlaff and Carrière 1985) and are predominantly associated with subvertical quartz veins and wall rock breccias in the Firstbrook Member of the Gowganda Formation. Some localized chalcopyrite mineralization is also present in the Nipissing intrusive suite, but appears to be minor.

ACKNOWLEDGMENTS

The authors thank Mississauga First Nation for their warm welcome, project blessing, teachings, closing ceremony and partnership in this project. Thank you for all these incredible experiences throughout the summer, and for making us feel like part of the community. Special thanks to Amanda Cress, Anthony Chiblow, Keith Sayers and traditional knowledge keeper Roger Daybutch for assisting and teaching us throughout the summer. The author would also like to thank Sagamok Anishnawbek First Nation, Serpent River First Nation, Thessalon First Nation and the Métis Nation of Ontario Superior North Shore Council for allowing the Ontario Geological Survey to map their traditional land use areas. Thanks to mapping assistants Maxwell Cain and Matthew Oelschlagel for their hard work during the mapping season. The authors also thank the MacIver family of Blind River, who hosted the crew at MacIver's Motel and Campground on Highway 17 during the 2022 field season. Thanks to R.M. Easton for discussions about the geology and his revisions to this summary.

REFERENCES

Bennett, G.B., Dressler, B.O. and Robertson, J.A. 1991. The Huronian Supergroup and associated intrusive rocks; Chapter 14 *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, p.549-591.

Card, K.D. 1978. Metamorphism of the middle Precambrian (Aphebian) rocks of the eastern Southern Province; *in* Metamorphism in the Canadian Shield, Geological Survey of Canada, Paper 78-10, p.269-282.

——— 1979. Regional geological synthesis, central Superior Province; *in* Current Research, Geological Survey of Canada, Paper 79-1A, p.87-90.

Corfu, F. and Andrews, A.J. 1986. A U–Pb age for mineralized Nipissing diabase, Gowganda, Ontario; Canadian Journal of Earth Sciences, v.23, p.107-109.

Davey, S., Bleeker, W., Kamo, S., Davis, D., Easton, R.M. and Sutcliffe, R.H. 2019. Ni-Cu-PGE potential of the Nipissing sills as part of the ca. 2.2 Ga Ungava large igneous province; *in* Targeted Geoscience Initiative: 2018 report of activities, Geological Survey of Canada, Open File 8549, p.404-419.

Hastie, E.C.G. and Vice, L.E.D. 2019. Preliminary geology of Scarfe and Cobden townships, Blind River area, Southern Province; *in* Summary of Field Work and Other Activities, 2019, Ontario Geological Survey, Open File Report 6360, p.13-1 to 13-11.

Hoffman, P.F. and Schrag, D.P. 2002. The snowball Earth hypothesis: Testing the limits of global change; Terra Nova, v.14, p.129-155.

Holland, H.D. 2006. The oxygenation of the atmosphere and oceans; Philosophical Transactions of the Royal Society B, v.361, p.903-915.

Junnila, R.M. and Young, G.M. 1995. The Paleoproterozoic upper Gowganda Formation, Whitefish Falls area, Ontario, Canada: Subaqueous deposits of a braid delta; Canadian Journal of Earth Sciences, v.32, p.197-209.

Kamo, S.L. 2020. Report on U-Pb ID-TIMS geochronology for the Ontario Geological Survey: Bedrock Mapping Projects, Ontario; internal report prepared for the Ontario Geological Survey, Jack Satterly Geochronology Laboratory, University of Toronto, Toronto, Ontario, 55p.

Ketchum, K.Y., Heaman, L.M., Bennett, G. and Hughes, D.J. 2013. Age, petrogenesis and tectonic setting of the Thessalon volcanic rocks, Huronian Supergroup, Canada; Precambrian Research, v.233, p.144-172.

Krogh, T.E., Davis, D.W. and Corfu, F. 1984. Precise U–Pb zircon and baddeleyite ages for the Sudbury Structure; *in* Geology and ore deposits of the Sudbury Structure, Ontario Geological Survey, Special Volume 1, p.431-446.

Lyons, T.W., Reinhard, C.T. and Planavsky, N.J. 2014. The rise of oxygen in the Earth's early ocean and atmosphere; Nature, v.506, p.307-315.

Ontario Geological Survey 2011. 1:250 000 scale bedrock geology of Ontario; Ontario Geological Survey, Miscellaneous Release—Data 126 – Revision 1.

——— 2022. Ontario Mineral Inventory; Ontario Geological Survey, Ontario Mineral Inventory (September 2022 update), online database.

Ontario Geological Survey and Golder Associates Ltd. 1996. Industrial mineral resource assessment of the Nipissing diabase, Highway 17 corridor from Massey to Blind River and North Channel Islands; Ontario Geological Survey, Mineral Deposits Circular 32, 30p.

Pearson, W.N., Bretzlaff, R.E. and Carrière, J.J. 1985. Copper deposits and occurrences in the north shore region of Lake Huron, Ontario; Geological Survey of Canada, Paper 83-28, 34p.

Petrus, J.A., Kenny, G.G., Ayer, J.A., Lightfoot, P.C. and Kamber, B.S. 2016. Uranium-lead zircon systematics in the Sudbury impact crater-fill: Implications for target lithologies and crater evolution; Journal of the Geological Society, v.173, p.59-75.

Rainbird, R.H. and Donaldson, J.A. 1988. Nonglaciogenic deltaic deposits in the Early Proterozoic Gowganda Formation, Cobalt Basin, Ontario; Canadian Journal of Earth Sciences, v.25, p.710-724.

Rasmussen, B., Bekker, A. and Fletcher, I.R. 2013. Correlation of the Paleoproterozoic glaciations based on U-Pb zircon ages for tuff beds in the Transvaal and Huronian supergroups; Earth and Planetary Science Letters, v.382, p.173-180.

Robertson, J.A. 1963. Geology of the Iron Bridge area; Ontario Department of Mines, Geological Report 17, 69p.

——— 1964. Geology of Scarfe, Mack, Cobden and Striker townships; Ontario Department of Mines, Geological Report 20, 89p.

Roscoe, S.M. 1973. The Huronian Supergroup, a Paleoaphebian succession showing evidence of atmospheric evolution; *in* Huronian stratigraphy and sedimentation, Geological Association of Canada, Special Paper 12, p.31-47.

Sutcliffe, C.N. 2020. U-Pb Geochronology report for samples from Northern Ontario by LA-ICPMS; internal report prepared for the Ontario Geological Survey, Jack Satterly Geochronology Laboratory, University of Toronto, Toronto, Ontario, 128p.

Zolnai, A.I., Price, R.A. and Helmstaedt, H. 1984. Regional cross section of the Southern Province adjacent to Lake Huron, Ontario: Implications for the tectonic significance of the Murray Fault zone; Canadian Journal of Earth Sciences, v.21, p.447-456.

15. Project ON-19-004. Trace Element Content of Gold Across Ontario: An Update on the Gold Fingerprinting Project



J.D. Melo-Gómez[1], E.C.G. Hastie[2], H.L. Gibson[1], K.T. Tait[3,4] and J.A. Petrus[5]

[1]Mineral Exploration Research Centre, Harquail School of Earth Sciences, Laurentian University, Sudbury, Ontario P3E 2C6
[2]Earth Resources and Geoscience Mapping Section, Ontario Geological Survey, Sudbury, Ontario P3E 6B5
[3]Department of Natural History, Royal Ontario Museum, Toronto, Ontario M5S 2C6
[4]Department of Earth Sciences, University of Toronto, Toronto, Ontario M5S 3B1
[5]Elemental Scientific Lasers LLC

INTRODUCTION

The goal of the Gold Fingerprinting project is to determine the unique elemental attributes and microchemical elemental associations within native gold in order to constrain its genesis, source, depositional processes and subsequent modification during metamorphism. Initiated in 2019, this project is a collaborative effort among the Metal Earth Initiative at Laurentian University, the Ontario Geological Survey (OGS) and the Royal Ontario Museum (ROM). The initial phase of the project was the development of rigorous sample preparation and analytical methods protocols. The second phase is the analysis of gold, starting with the gold deposits of Ontario, which have been an essential driver for the province's economy and are the focus of this report.

In this article, we report the trace element content of native gold from representative samples covering most of Ontario's gold deposits. Previous work, which examined the trace element content in gold and its alloys (Guerra and Calligaro 2004; Chapman et al. 2021), has linked these variations to individual deposits (Watling, Scadding and Dixon 2009; Velasquez 2014), to metallogenic belt-scale processes (Hastie et al. 2022), and to different deposit types, such as orogenic gold, epithermal or volcanogenic massive sulphide (Gas'kov 2017; Liu et al. 2021).

The present study is part of the MSc thesis research of the senior author and builds on the work of Hastie et al. (2020) and Melo-Gómez et al. (2021), including the application of modern *in-situ* techniques, such as laser ablation inductively coupled plasma mass spectrometry (LA-ICP–MS), to determine the concentration of a suite of 46 elements and isotopes. The deposits studied include world-class localities, such as the Abitibi greenstone belt (Gosselin and Dubé 2005; Monecke et al. 2017; Dubé and Mercier-Langevin 2020), the Red Lake greenstone belt (Dubé et al. 2004; Harris et al. 2006; MacDonald and Malegus 2021) and areas that have recently received interest and increased exploration, such as the Geraldton–Beardmore (Tóth 2018) and Michipicoten greenstone belts (Wehrle 2020). The results presented herein will be included in a planned online Gold Fingerprinting database that will be freely available to the public (Hastie et al. 2020). It is anticipated that this database will assist exploration, as well as contribute to our understanding of the metallogeny of gold in Ontario.

Summary of Field Work and Other Activities, 2022,
Ontario Geological Survey, Open File Report 6390, p.15-1 to 15-11.

© King's Printer for Ontario, 2022

Table 15.1. Average limit of detection (LOD), in parts per million (ppm), for each isotope measured in native gold analyzed by LA-ICP–MS.

Isotope	LOD	Isotope	LOD	Isotope	LOD	Isotope	LOD
^{7}Li	0.43	^{57}Fe	8.64	^{101}Ru	17.75	^{185}Re	1.80
^{24}Mg	1.05	^{59}Co	0.09	^{103}Rh	0.19	^{189}Os	0.43
^{27}Al	1.05	^{60}Ni	3.39	^{105}Pd	0.04	^{193}Ir	0.05
^{29}Si	502.48	^{63}Cu	0.24	^{107}Ag	0.42	^{195}Pt	14.55
^{31}P	93.25	^{66}Zn	0.76	^{108}Pd	0.05	^{197}Au	0.43
^{34}S	375.60	^{71}Ga	0.11	^{111}Cd	0.10	^{202}Hg	2.42
^{43}Ca	395.77	^{72}Ge	78.81	^{115}In	0.63	^{205}Tl	0.13
^{45}Sc	0.47	^{75}As	8.59	^{118}Sn	1.24	^{206}Pb	13.20
^{47}Ti	2.08	^{82}Se	8.99	^{121}Sb	0.04	^{207}Pb	4.57
^{51}V	0.17	^{90}Zr	1.31	^{125}Te	10.87	^{208}Pb	20.45
^{52}Cr	2.12	^{93}Nb	0.04	^{181}Ta	0.002	^{209}Bi	4.39
^{55}Mn	1.85	^{95}Mo	0.15	^{182}W	0.84	^{238}U	11.63

METHODS

Following the results of Hastie et al. (2020) and Melo-Gómez et al. (2021), the current phase of the Gold Fingerprinting project focussed on determining the trace and ultra-trace element composition of native gold. As these elements are present in very low quantities, LA-ICP–MS analyses were performed following an in-house–developed method to minimize contamination while maximizing sensitivity and data quality.

The grain mounting and previous data acquisition protocols are described in Melo-Gómez et al. (2021). The LA-ICP–MS analyses were performed at the Mineral Exploration Research Centre Isotope Geochemistry Laboratory (Sudbury, Ontario) to obtain quantitative concentrations of trace elements in the native gold. The analyses were performed with a Photon Machines Analyte G2 ArF excimer laser with 193 nm wavelength coupled to a Thermo Scientific™ iCap™ TQ ICP–MS in single quad mode. The ablation parameters were an energy density of 5 J/cm^2, a laser frequency of 7 Hz, a spot size of 50 µm (20 µm for smaller samples), and a background measurement time of 30 s followed by 30 s on the sample. The elemental suite acquired is as follows: ^{7}Li, ^{24}Mg, ^{27}Al, ^{29}Si, ^{31}P, ^{34}S, ^{43}Ca, ^{45}Sc, ^{47}Ti, ^{51}V, ^{52}Cr, ^{55}Mn, ^{57}Fe, ^{59}Co, ^{60}Ni, ^{63}Cu, ^{66}Zn, ^{75}As, ^{82}Se, ^{90}Zr, ^{93}Nb, ^{95}Mo, ^{101}Ru, ^{103}Rh, ^{105}Pd, ^{107}Ag, ^{108}Pd, ^{111}Cd, ^{115}In, ^{118}Sn, ^{121}Sb, ^{125}Te, ^{181}Ta, ^{182}W, ^{185}Re, ^{189}Os, ^{193}Ir, ^{195}Pt, ^{197}Au, ^{202}Hg, ^{205}Tl, ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{209}Bi and ^{238}U. Visible inclusions and fractures were avoided, and major micro-inclusions visible in the time-resolved signal and surface contamination were removed during data processing.

Data were reduced using Iolite Software v4 (Paton et al. 2011). External standards used to calibrate the analytes were the synthetic glasses NIST SRM 610 (Jochum et al. 2011), USGS basaltic glass GSE-1G (Jochum et al. 2005b) and the artificial sulphide FeS1 (Savard et al. 2018); with the reference values taken from GeoReM (Jochum et al. 2005a). An in-house natural gold specimen was also used as part of the calibration. The synthetic gold standards AuRM1 and AuRM2 (Milidragovic, Beaudoin and Jackson 2016) were used for quality control for the trace elements, as well as the previously obtained electron probe microanalyzer (EPMA) data for gold, silver, copper and mercury. This quality assurance–quality control (QA/QC) procedure indicated good accuracy and precision (below 15%) for the trace elements discussed herein and a good correlation with EPMA data for major and minor elements.

Table 15.1 presents the average limit of detection (LOD) for each measured isotope, in parts per million (ppm), calculated using the methods proposed by Pettke et al. (2012). The background signals for silicon, phosphorus, sulphur and calcium were too high and these elements are not included in the

analysis. A total of 201 samples from 69 mines and deposits from across Ontario were analyzed. Where size permitted, 10 spots were measured across and along each grain to identify the homogeneity of trace elements in gold, resulting in the analysis of 1656 points in all the samples.

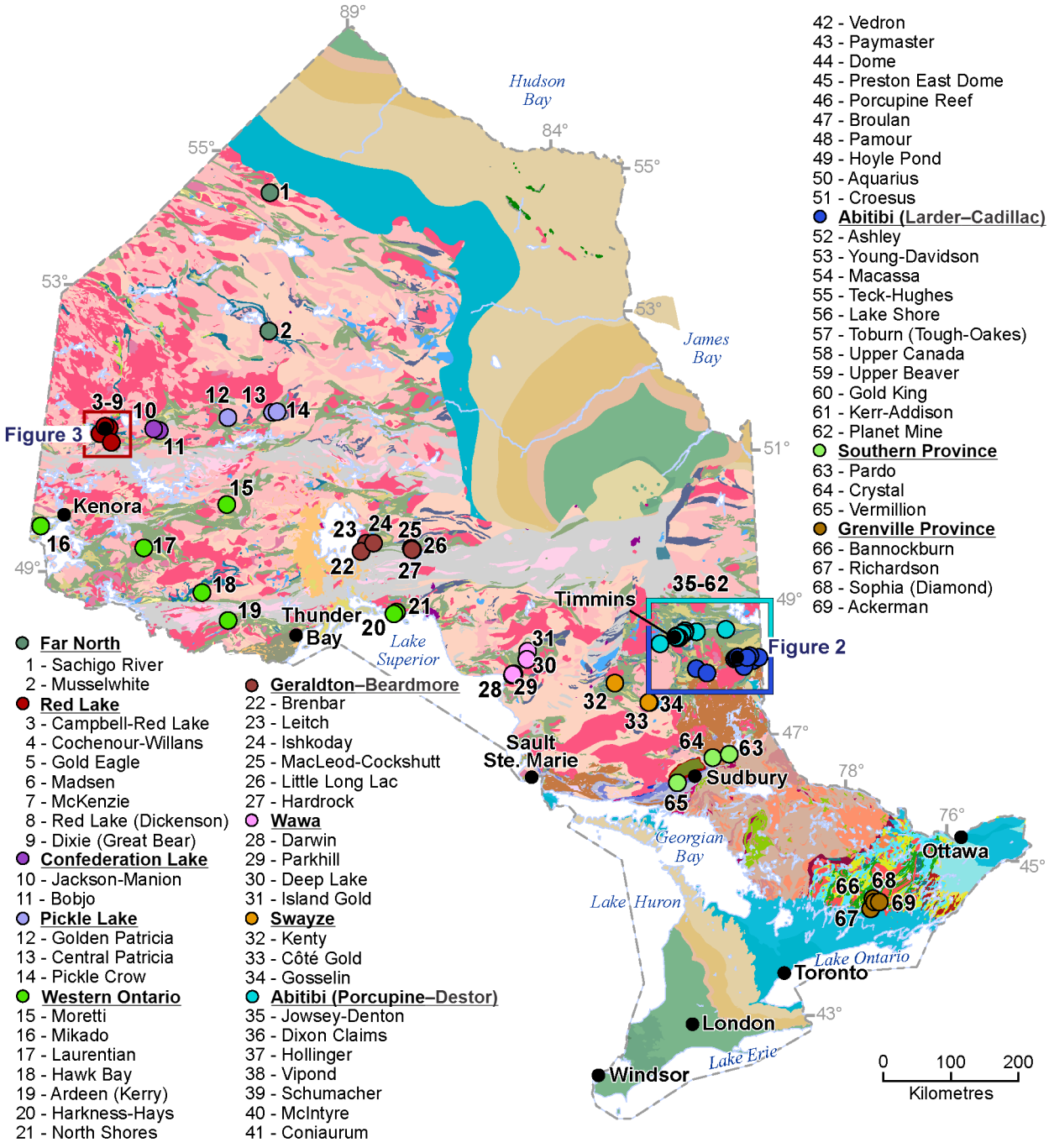


Figure 15.1. Geological map of Ontario, with simplified bedrock units, displaying the location of mines and deposits for which data are included in this report. The legend shows the name for each deposit or mine grouped according to their proximity to mining camps or greenstone belts. For an enlargement of the Abitibi area, *see* Figure 15.2, and for the Red Lake area, *see* Figure 15.3. Refer to Ontario Geological Survey (2011) for a detailed geological legend.

RESULTS

The samples reported herein were obtained from the Royal Ontario Museum (ROM) collection, individuals and companies. The sample locations are shown in Figure 15.1 and are grouped based on the mining camp or greenstone belt where they are located, or are close to. Figures 15.2 and 15.3 are an enlargement of the Abitibi and Red Lake greenstone belt areas, respectively. The Abitibi greenstone belt samples were subdivided according to their proximity to the Porcupine–Destor and Larder–Cadillac fault zones (*see* Figure 15.2).

Ontario native gold samples are characterized by their homogeneity with respect to gold, silver, copper and mercury, as observed in scanning electron microscope (SEM) and EPMA analyses (Melo-Gómez et al. 2021). Apart from these major and minor elements, the gold samples have concentrations commonly over the detection limit for antimony, palladium, cadmium and bismuth. The other elements are rarely detected and thus are not discussed further. The correlations between gold and silver, copper, mercury and antimony are illustrated in Figure 15.4. The bivariate plots show a negative correlation of 1:1 between gold and silver and a positive correlation with copper (*see* Figures 15.4A and 15.4B) consistent with the solid solution between these elements (Boyle 1979; Chapman, Mortenson and LeBarge 2011; Townley et al. 2003). Values for mercury and antimony (*see* Figures 15.4C and 15.4D), as well as palladium and cadmium (plots not shown), however, show no correlation with increasing gold concentration.

The copper, mercury, antimony, palladium and cadmium results, plotted in the boxplot shown in Figure 15.5, are grouped based on the distribution shown in Figure 15.1. The copper concentrations vary between tens to thousands of ppm in gold, with the highest being in samples from the Grenville Province, with a mean of 541.3 ppm Cu and the lowest from samples near Sudbury and in the Southern Province with a mean of 206.3 ppm Cu. The Porcupine–Destor area samples have a low mean of 229.8 ppm Cu, whereas the Larder–Cadillac area samples have a mean of 441.7 ppm Cu.

The range for mercury concentrations is larger than for copper, with a maximum of 26 426 ppm Hg and a minimum of 1.3 ppm Hg. The samples from the Southern Province, as a group, have the highest mercury concentration with a mean of 2006 ppm Hg; however, there is possibly more than one population in this group. The Porcupine–Destor and Larder–Cadillac area samples have means of 830.3 and 1776.6 ppm Hg, respectively; however, the Upper Beaver sample is an outlier with a mean of 68 899 ppm Hg. The samples from the Pickle Lake, Wawa and Confederation Lake areas tend to have lower values with means of 249.2, 119.9 and 66.2 ppm Hg, respectively.

Antimony shows the broadest range of values, spanning several orders of magnitude. Gold from the Red Lake camp is characterized by a high median of 18.5 ppm Sb, followed by gold from the Geraldton–Beardmore area where samples have a mean of 10.2 ppm Sb. Samples from the Madsen Mine have distinctively lower antimony values than samples from the rest of the mines in the Red Lake camp. Conversely, samples from the Larder–Cadillac and Swayze areas have the lowest antimony, with mean values of 0.050 and 0.037 ppm Sb, respectively.

In the case of palladium, because of accuracy and precision issues with ^{108}Pd, only the isotope ^{105}Pd is presented herein. Gold from the Southern Province near Sudbury has high palladium concentrations, with a median of 20.2 ppm Pd, but with concentrations as high as 691.2 ppm Pd. Samples from Upper Beaver, Côté Gold and Gosselin also show moderately high palladium values, with means of 15.1, 4.79 and 1.52 ppm Pd, respectively. Cadmium shows a similar trend, with the Southern Province samples having the highest mean of 0.81 ppm Cd, whereas samples from the Larder–Cadillac area have the lowest concentrations, with a mean of 0.076 ppm Cd.

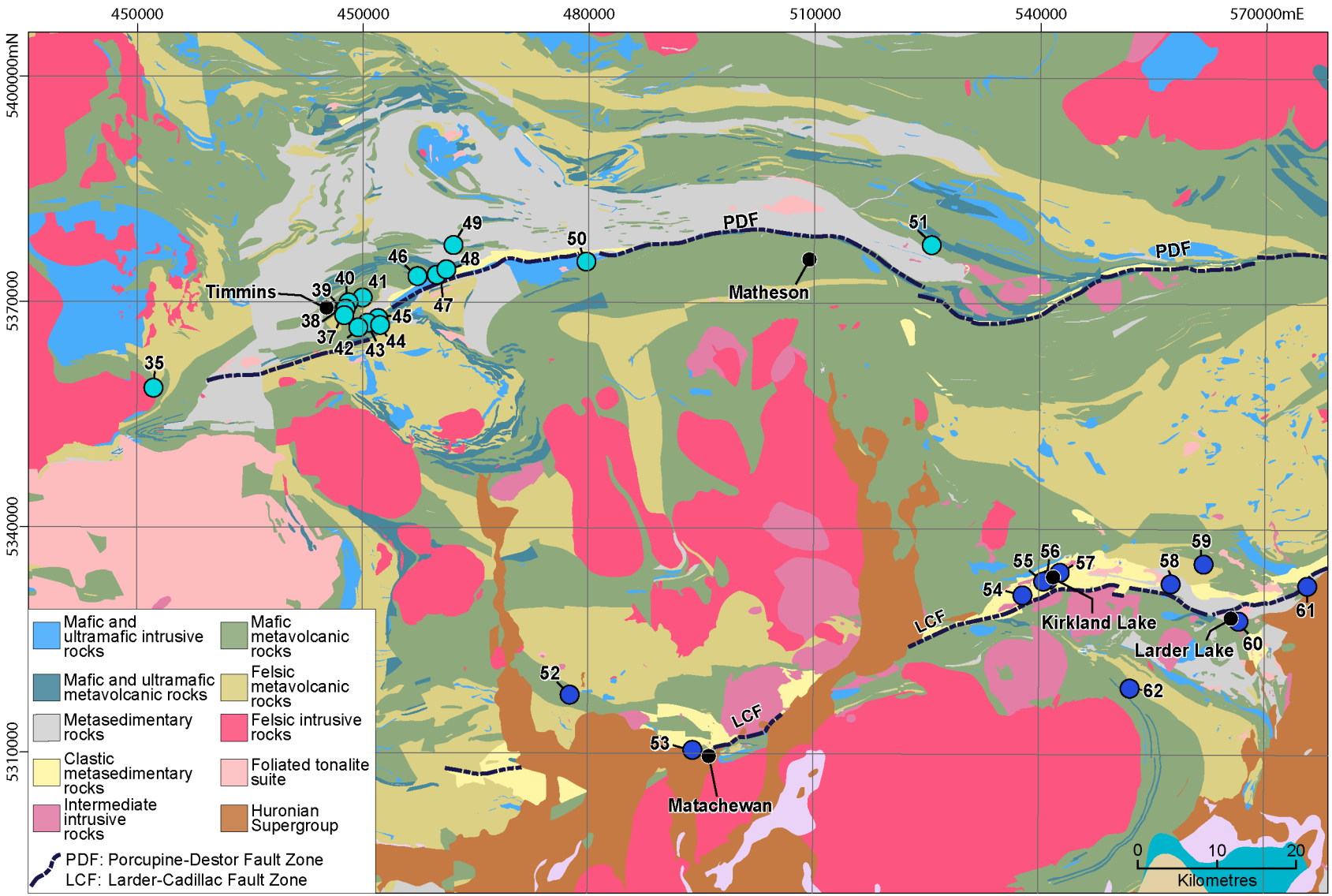


Figure 15.2. Simplified geological map showing the location of Abitibi greenstone belt samples along the Porcupine–Destor fault zone (PDF) and the Larder–Cadillac fault zone (LCF). Mines and/or deposits are numbered and are keyed the list provided in Figure 15.1 (note, deposit 36 is not shown on this figure). Geology *from* Ontario Geological Survey (2011) and *from* Dubé and Mercier-Langevin (2020). The Universal Transverse Mercator (UTM) co-ordinates are provided in North American Datum 1983 (NAD83) in Zone 17.

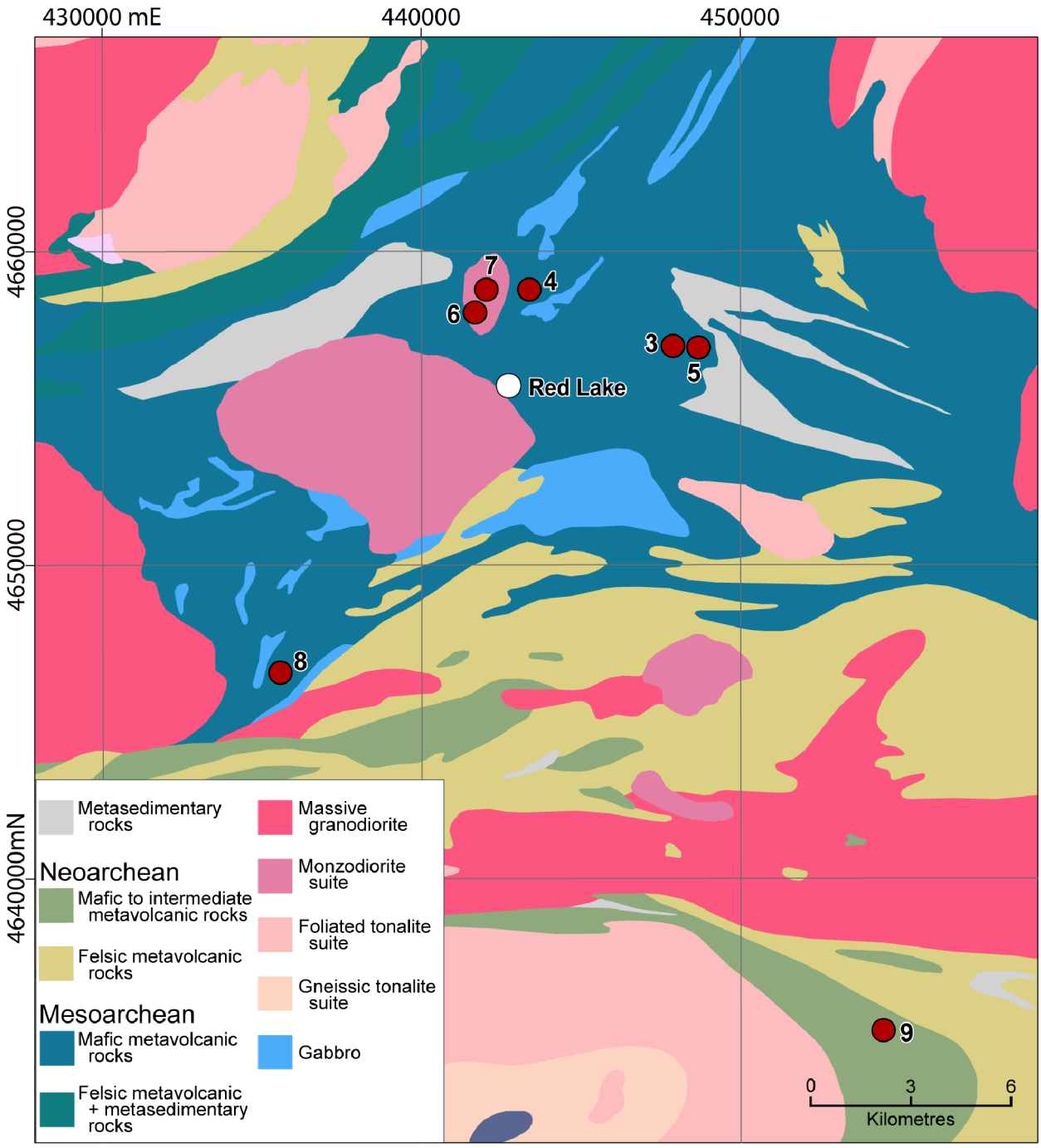


Figure 15.3. Simplified geological maps showing the location of the deposits and mines in the Red Lake area included in this study. Mines and/or deposits are numbered and are keyed the list provided in Figure 15.1. Geology *from* Ontario Geological Survey (2011). The Universal Transverse Mercator (UTM) co-ordinates are provided in North American Datum 1983 (NAD83) in Zone 15.

CONCLUSIONS AND FUTURE WORK

Individual gold grains from across the province of Ontario have compositional homogeneity where the analytical results exclude macro inclusions. The behaviour of silver and copper in gold suggests a strong control of these concentrations based on the quantity of gold as described by Boyle (1979) and Chapman et al. (2000). However, the concentrations of mercury, antimony, palladium and cadmium are independent of gold content and may be related to other geological factors. For example, gold from the Red Lake area commonly has a high content of antimony, but lower content of copper, palladium and cadmium when compared to gold from elsewhere in the province. In addition, gold from deposits on or close to the Porcupine–Destor fault zone has a different microchemical signature than deposits on or close to the Larder–Cadillac fault zone (Melo-Gómez et al. 2021). The trace element data support this, as samples from the Porcupine–Destor fault zone have higher concentrations of antimony, cadmium and palladium, but lower copper and mercury, compared to samples from the Larder–Cadillac fault zone.

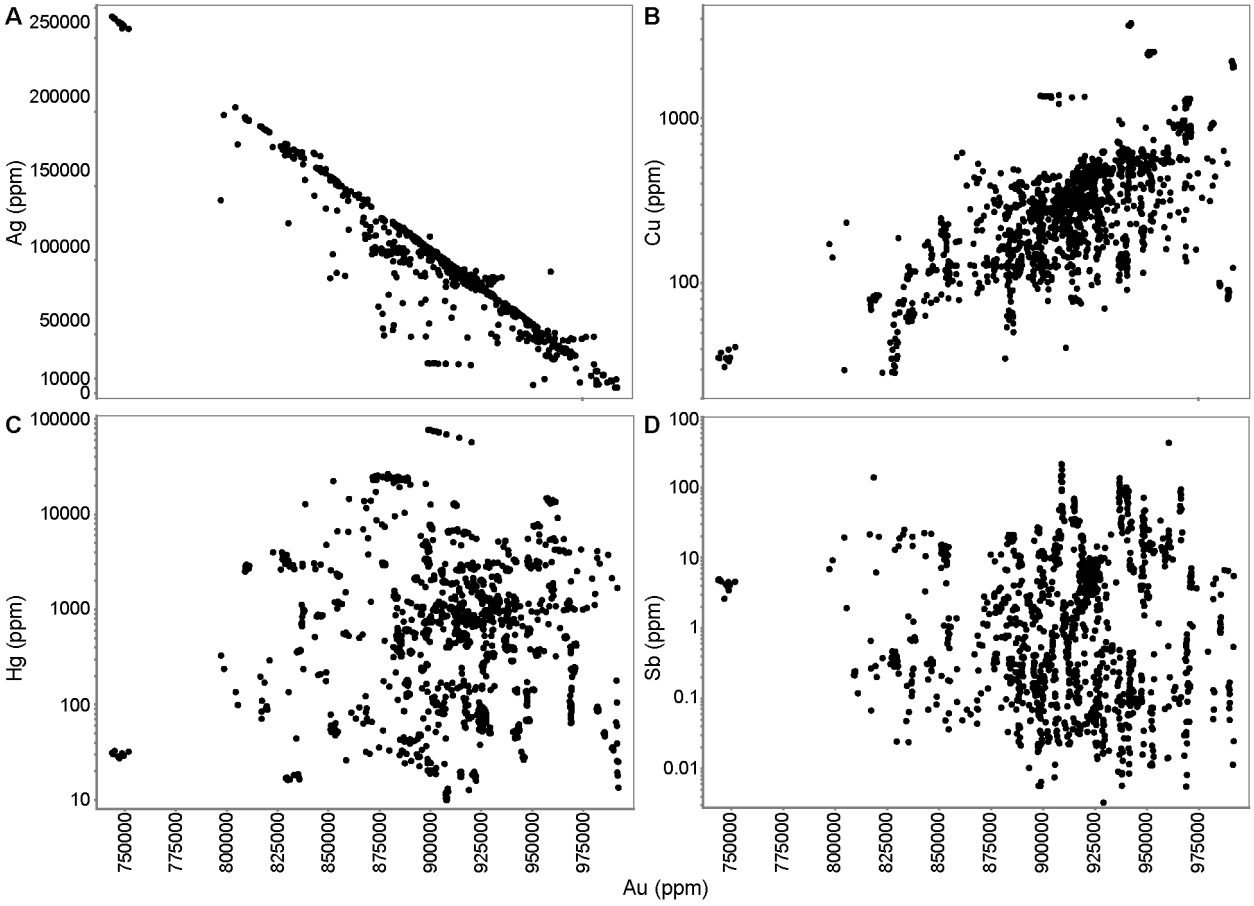


Figure 15.4. Bivariate LA-ICP–MS plots showing the correlation between **A)** gold (Au) and silver (Ag), **B)** gold (Au) and copper (Cu), **C)** gold (Au) and mercury (Hg), and **D)** gold (Au) and antimony (Sb). The units are in part per million (ppm), and for B), C) and D), the Y-axis is on a logarithmic scale. Note the correlation between gold and silver (Au–Ag) and gold and copper (Au–Cu).

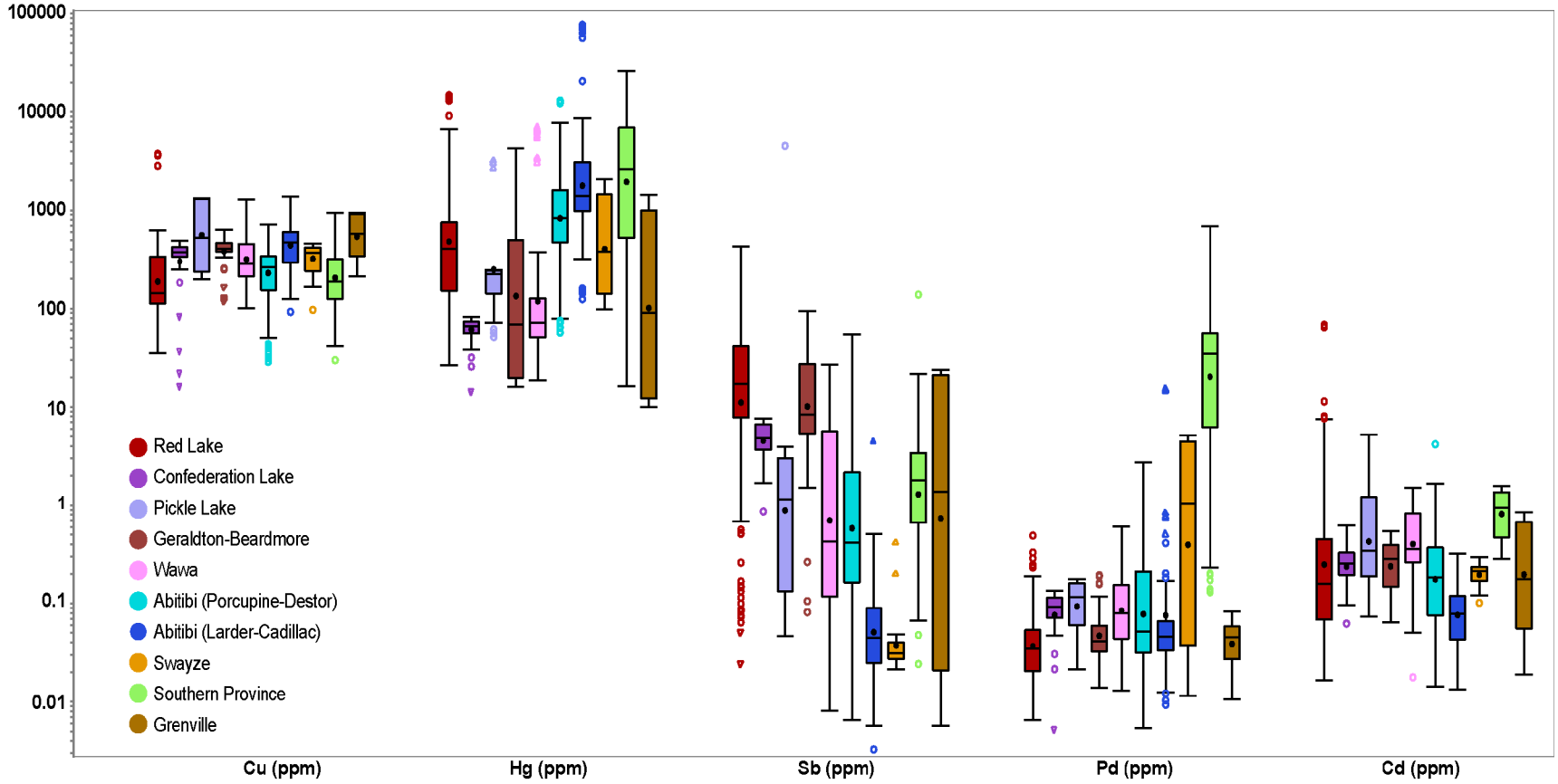


Figure 15.5. Box and whisker plots showing the variability in copper, mercury, antimony, palladium and cadmium (Cu, Hg, Sb, Pd and Cd, respectively) in native gold for each studied area, which are each represented by a different colour. The horizontal line (within the colour-filled rectangle) represents the median; the solid black dot (within the colour-filled rectangle) represents the mean; and the box represents the 25th to 75th percentile of the data. Whiskers are drawn to the last data point, which is 1.5 times the box length from the maximum and minimum. Open circles are outliers (within 3 box lengths), and open triangles are extreme outliers (beyond 3 box lengths).

Future work will include describing and interpreting the trace element data presented herein in order to fingerprint gold from deposits across Ontario. These interpretations will be based on geological associations, such as host rock, age, metamorphism and crustal architecture. These data will be recorded in a planned global gold database that will be freely available (Hastie et al. 2020). The database will aid exploration and constrain processes in gold ore systems. The data will also serve as a reference for forensic geology, archaeology or other areas of research that include an emphasis on gold.

ACKNOWLEDGMENTS

This project is supported by the Ontario Geological Survey, the Royal Ontario Museum and the Metal Earth Initiative through the Mineral Exploration Research Centre (MERC) and the Harquail School of Earth Sciences at Laurentian University. This is Harquail School of Earth Sciences, Mineral Exploration Research Centre–Metal Earth publication number MERC-ME-2022-35. This work is part of a Master of Science thesis project by Julian Melo-Gómez in the Harquail School of Earth Sciences at Laurentian University under the supervision of Dr. Harold Gibson and Dr. Evan Hastie. Special thanks to Katherine Dunnell at the Royal Ontario Museum for her hard work organizing and sampling material from their collection. Assistance provided by Dr. Jeffrey Marsh from the Isotope Geochemistry Laboratory at MERC is greatly appreciated, especially in the acquisition and quality control of the LA-ICP–MS data presented herein. Special thanks are also offered to companies and individuals for donating samples to the current data set shown above and for samples not yet analyzed. Companies: Alamos Gold Inc., Canadian Gold Miner Corp., IAMGOLD Corp., Inventus Mining Corp., Evolution Mining Limited, Kinross Gold Corp., Newmont Corp. and Transition Metals Corp. Individuals: Dorothy Campbell, Harold Gibson, Craig Green, Sheree Hinz, Tom Hart, Evan Hastie, Peter Karelse, Rohan Millar, Jeremy Richards and Ross Sherlock. J.D.M-G. wrote the article with contributions from all other authors. J.D.M-G. processed the LA-ICP–MS data. J.D.M-G. interpreted the data with assistance from E.C.G.H. and H.L.G. E.C.G.H., H.L.G., K.T.T. and J.A.P. jointly conceived the study.

REFERENCES

Boyle, R.W. 1979. The geochemistry of gold and its deposits; Geological Survey of Canada, Bulletin 280, 584p.

Chapman, R.J., Banks, D.A., Styles, M.T., Walshaw, R.D., Piazolo, S., Morgan, D.J., Grimshaw, M.R., Spence-Jones, C.P., Matthews, T.J. and Borovinskaya, O. 2021. Chemical and physical heterogeneity within native gold: Implications for the design of gold particle studies; Mineralium Deposita, v.56, p.1563-1588. doi.org/10.1007/s00126-020-01036-x

Chapman, R.J., Leake, R.C., Moles, N.R., Earls, G., Cooper, C., Harrington, K. and Berzins, R. 2000. The application of microchemical analysis of alluvial gold grains to the understanding of complex local and regional gold mineralization: A case study in the Irish and Scottish Caledonides; Economic Geology, v.95, p.1753-1773.

Chapman, R.J., Mortensen, J.K. and LeBarge, W.P. 2011. Styles of lode gold mineralization contributing to the placers of the Indian River and Black Hills Creek, Yukon Territory, Canada as deduced from microchemical characterization of placer gold grains; Mineralium Deposita, v.46, p.881-903.

Dubé, B. and Mercier-Langevin, P. 2020. Gold deposits of the Archean Abitibi greenstone belt, Canada; *in* Geology of the world's major gold deposits and provinces, Society of Economic Geologists, Special Publication No.23, p.669-708.

Dubé, B., Williamson, K., McNicoll, V., Malo, M., Skulski, T., Twomey, T. and Sanborn-Barrie, M. 2004. Timing of gold mineralization at Red Lake, northwestern Ontario, Canada: New constraints from U-Pb geochronology at the Goldcorp high-grade zone, Red Lake mine, and the Madsen mine; Economic Geology, v.99, p.1611-1641.

Gas'kov, I.V. 2017. Major impurity elements in native gold and their association with gold mineralization settings in deposits of Asian folded areas; Russian Geology and Geophysics, v.58, p.1080-1092.

Gosselin, P. and Dubé, B. 2005. Gold deposits of Canada: Distribution, geological parameters and gold content; Geological Survey of Canada, Open File 4896, 105p.

Guerra, M.F. and Calligaro, T. 2004. Gold traces to trace gold; Journal of Archaeological Science, v.31, p.1199-1208.

Harris, J.R., Sanborn-Barrie, M., Panagapko, D.A., Skulski, T. and Parker, J.R. 2006. Gold prospectivity maps of the Red Lake greenstone belt: Application of GIS technology; Canadian Journal of Earth Sciences, v.43, p.865-893.

Hastie, E.C.G., Kontak, D.J., Lafrance, B., Petrus, J.A., Sharpe, R. and Fayek, M. 2022. Evaluating geochemical discriminants in Archean gold deposits: A Superior Province perspective with an emphasis on the Abitibi greenstone belt; Economic Geology, published online August 17, 2022. doi.org/10.5382/econgeo.4979

Hastie, E.C.G., Petrus, J.A., Gibson, H.L. and Tait, K.T. 2020. Gold Fingerprinting: Using major and trace elements associated with native gold to work toward a global gold database; *in* Summary of Field Work and Other Activities, 2020, Ontario Geological Survey, Open File Report 6370, p.10-1 to 10-10.

Jochum, K.P., Nohl, U., Herwig, K., Lammel, E., Stoll, B. and Hofmann, A.W. 2005a. GeoReM: A new geochemical database for reference materials and isotopic standards; Geostandards and Geoanalytical Research, v.29, p.333–338. doi.org/10.1111/j.1751-908X.2005.tb00904.x, online database available at http://georem.mpch-mainz.gwdg.de [accessed November 9, 2022]

Jochum, K.P., Weis, U., Stoll, B., Kuzmin, D., Yang, Q., Raczek, I., Jacob, D.E., Stracke, A., Birbaum, K., Frick, D.A. and Günther, D. 2011. Determination of reference values for NIST SRM 610–617 glasses following ISO guidelines; Geostandards and Geoanalytical Research, v.35, p.397-429.

Jochum, K.P., Willbold, M., Raczek, I., Stoll, B. and Herwig, K. 2005b. Chemical characterisation of the USGS reference glasses GSA-1G, GSC-1G, GSD-1G, GSE-1G, BCR-2G, BHVO-2G and BIR-1G using EPMA, ID-TIMS, ID-ICP-MS and LA-ICP-MS; Geostandards and Geoanalytical Research, v.29, p.285-302.

Liu, H., Beaudoin, G., Makvandi, S., Jackson, S. and Huang, X. 2021. Multivariate statistical analysis of trace element compositions of native gold from orogenic gold deposits: Implication for mineral exploration; Ore Geology Reviews, v.131, paper 104061. doi.org/10.1016/j.oregeorev.2021.104061

MacDonald, P.J. and Malegus, P.M. 2021. Introduction to the Red Lake bedrock geology mapping compilation project, northwestern Ontario; *in* Summary of Field Work and Other Activities, 2021, Ontario Geological Survey, Open File Report 6380, p.9-1 to 9-5.

Melo-Gómez, J.D., Hastie, E.C.G., Gibson, H.L., Tait, K.T. and Petrus, J.A. 2021. Gold fineness across Ontario: An update on the Gold Fingerprinting Project; *in* Summary of Field Work and Other Activities, 2021, Ontario Geological Survey, Open File Report 6380, p.13-1 to 13-9.

Milidragovic, D., Beaudoin, G. and Jackson, S. 2016. In-situ trace element characterization of three gold reference materials using EPMA and LA-ICP-MS; Geological Survey of Canada, Open File 8096, 26p. and data files. doi.org/10.4095/299097

Monecke, T., Mercier-Langevin, P., Dubé, B. and Hannington, M. 2017. Archean base and precious metal deposits, southern Abitibi greenstone belt, Canada; Reviews in Economic Geology, v.19, p.1-5.

Ontario Geological Survey 2011. 1:250 000 scale bedrock geology of Ontario; Ontario Geological Survey, Miscellaneous Release—Data 126 – Revision 1.

Paton, C., Hellstrom, J., Paul, B., Woodhead, J. and Hergt, J. 2011. Iolite: Freeware for the visualisation and processing of mass spectrometric data; Journal of Analytical Atomic Spectrometry, v.26, p.2508-2518. doi.org/10.1039/c1ja10172b

Pettke, T., Oberli, F., Audetat, A., Guillong, M., Simon, A.C., Hanley, J.J. and Klemm, L.M. 2012. Recent developments in element concentration and isotope ratio analysis of individual fluid inclusions by laser ablation single and multiple collector ICP-MS; Ore Geology Reviews, v.44, p.10-38. doi.org/10.1016/j.oregeorev.2011.11.001

Savard, D., Bouchard-Boivin, B., Barnes, S-J. and Garbe-Schönberg, D. 2018. UQAC-FeS: A new series of base metal sulfide quality control reference material for LA-ICP-MS analysis; *in* Proceedings of the 10th International Conference on the Analysis of Geological and Environmental Materials, Sydney, Australia, p.8-13.

Tóth, Z. 2018. The geology of the Beardmore-Geraldton belt, Ontario, Canada: Geochronology, tectonic evolution and gold mineralization; unpublished PhD thesis, Laurentian University, Sudbury, Ontario, 276p.

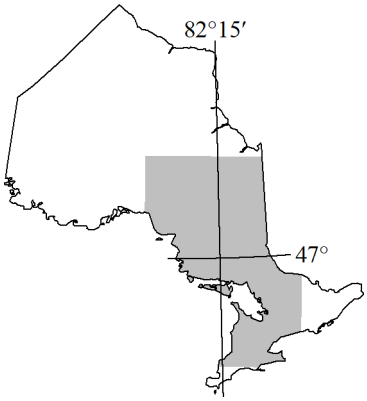
Townley, B.K., Hérail, G., Maksaev, V., Palacios, C., de Parseval, P., Sepulveda, F., Orellana, R., Rivas, P. and Ulloa, C. 2003. Gold grain morphology and composition as an exploration tool: Application to gold exploration in covered areas; Geochemistry: Exploration, Environment, Analysis, v.3, p.29-38.

Velasquez, A. 2014. Trace element analysis of native gold by laser ablation ICP-MS: A case study in greenstone-hosted quartz-carbonate vein ore deposits, Timmins, Ontario; unpublished MSc thesis, The University of British Columbia, Okanagan, British Columbia, 58p.

Watling, R.J., Scadding, C.J. and Dixon, R. 2009. Gold – Identifying its provenance; Chapter 88A *in* Expert evidence: Law, practice, procedure and advocacy, 4th ed., Lawbook Company, Sydney, Australia, 76p.

Wehrle, E.A. 2020. Gold mineralization in the Archean Wawa gold corridor, Wawa, Ontario; unpublished PhD thesis, University of Windsor, Windsor, Ontario, 148p.

16. Summary of Geophysical Projects and Activities



S. Biswas[1] and J. Evangelatos[1]

[1]Earth Resources and Geoscience Mapping Section, Ontario Geological Survey

INTRODUCTION

Geophysical services, including imaging, data compilation, interpretation and computational models, were provided in support of bedrock mapping, groundwater and Resident Geologist programs. Data sets from 2 airborne gravity and magnetic surveys have been donated by Nuclear Waste Management Organization (NWMO). These data sets are under review and being prepared for public release.

SUPPORT FOR THE BEDROCK GEOLOGY MAPPING PROGRAM

Unlike the previous 2 years, the Ontario Geological Survey (OGS) mapping program for the 2022 field season returned to normal levels. Support consisted of analysis of existing geophysical layers already provided for projects, the creation of suites of images for new projects and comparative reviews of geological maps with respect to geophysical data prior to publication.

Ternary magnetic images continued to be generated in support of mapping. These products are composite images of the reduced-to-pole residual magnetic intensity (RMI), first vertical derivative of the pole-reduced RMI and second vertical derivative of the pole-reduced RMI, and are created by assigning red, green and blue palettes, respectively. The ternary magnetic images effectively display magnetic fabrics, low amplitude responses and other features in fine detail.

Geophysical support was provided for the following new or ongoing bedrock mapping projects:

- Red Lake bedrock geology compilation project
- Animikie Group and Logan igneous suite compilation project
- North Caribou greenstone belt geology compilation project

ACQUISITION OF NEW GROUND GRAVITY DATA

An approximately 3480-station ground gravity survey is planned in the Guelph area to support the Guelph three-dimensional (3-D) sediment mapping project (Figure 16.1). The 100 m spaced stations will be distributed over 27 profiles along the roads in the region covering approximately 1450 km^2. The survey will complement existing ground gravity surveys in the Orangeville–Fergus, Kitchener–Waterloo Region, and Niagara Peninsula areas. The survey area is underlain by southwest-dipping bedrock of the Queenston Formation, above which are the Clinton–Cataract groups, Lockport Group and Salina Group.

Summary of Field Work and Other Activities, 2022,
Ontario Geological Survey, Open File Report 6390, p.16-1 to 16-6.

© King's Printer for Ontario, 2022

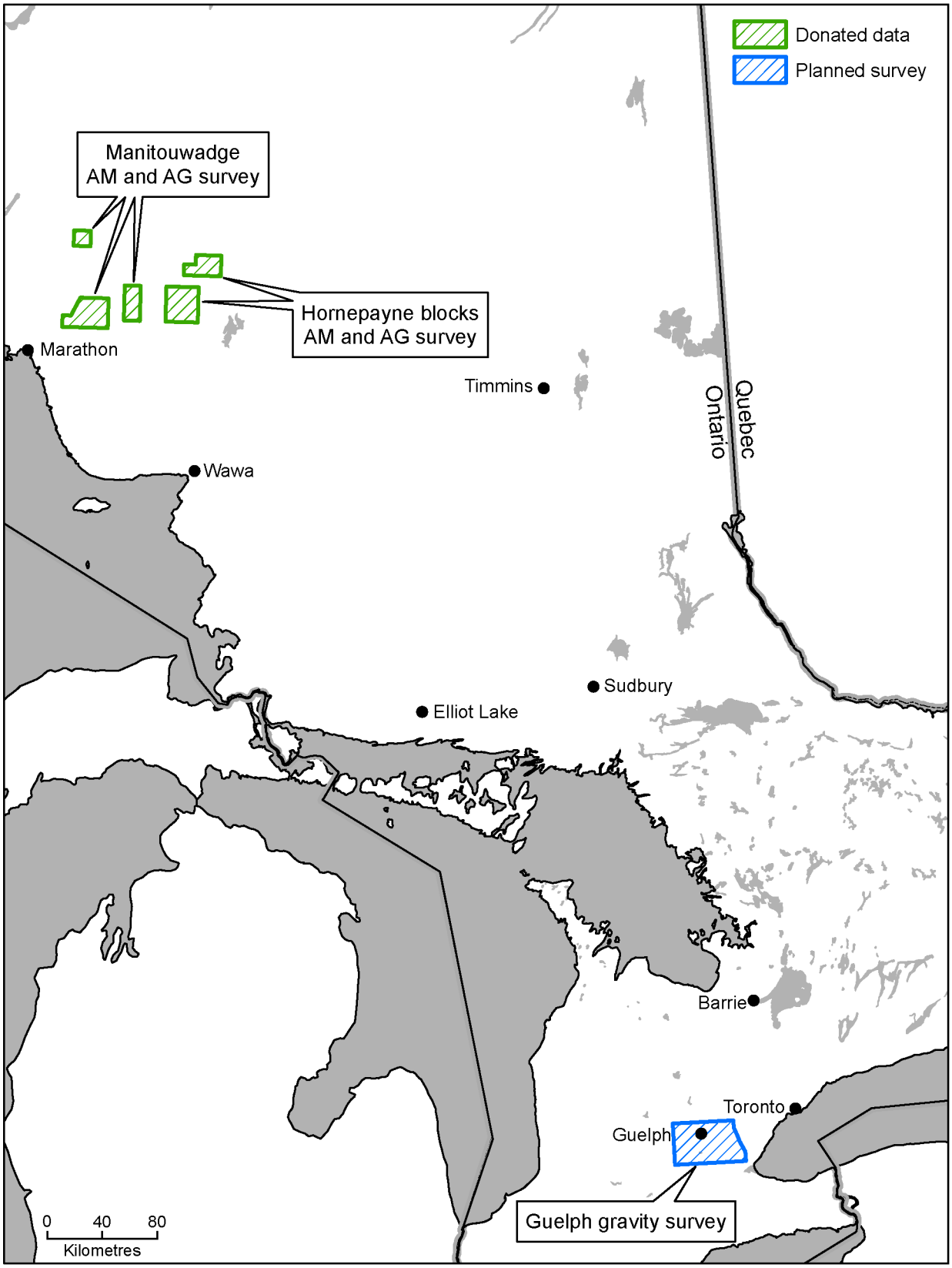


Figure 16.1. Locations of donated airborne geophysical surveys and upcoming planned ground gravity survey. Abbreviations: AG, airborne gravity; AM, airborne magnetic.

The sediment cover in the area varies from negligible in the east to 100 m in the southwest. The survey results, expected in early 2023, will be initially used to identify potential thalwegs and guide the placement of boreholes required to map and characterize subsurface sediments forming the regional and local aquifers and aquitards. Subsequently, the gravity data from the survey will be used to develop two-dimensional (2-D) models of sedimentary layers and underlying bedrock along select profiles to support the 3-D sediment mapping project in the Guelph area.

PLANNED GEOPHYSICAL DATA RELEASES

The OGS plans to reprocess 2 donated data sets commissioned by the NWMO and flown in 2015. Each data set consists of a joint airborne magnetic and gravity survey – the Hornepayne and Manitouwadge area surveys (*see* Figure 16.1). The Hornepayne survey comprises 12 694 line-kilometres and covers 2 separate blocks with a total area of approximately 1240 km^2. The Manitouwadge survey consists of 13 957 line-kilometres over 3 blocks and extends over a total area of approximately 1340 km^2.

SUPPORT FOR THE GROUNDWATER PROGRAM

Work is continuing to support three-dimensional (3-D) sediment mapping project (Burt 2013) in the Niagara Peninsula. The models, generated using GM-SYS 2-D modelling software, for the Bell Road gravity profile, the Morris Road gravity profile and the Regional Road 20 (RR20) gravity profile (Figure 16.2) were presented in Rainsford and Biswas (2018), Rainsford, Biswas and Larsen (2020) and Rainsford and Biswas (2021), respectively. In 2022, work is in progress to model the residual Bouguer gravity, calculated using a density of 2.1 g/cc, along Forks Road in the southern part of the study area. All 4 residual gravity profiles are shown in Figure 16.3 for comparison.

The Forks Road gravity profile is nearly 42 km long. The Forks Road gravity profile starts as a low gravity anomaly in the western end, is characterized by a broad high gravity anomaly in the western part, followed by moderately varying low gravity anomaly in the central part, another high gravity anomaly farther east and a low gravity anomaly at the eastern end (*see* Figure 16.3). The 1.86 mGal high gravity anomaly at profile distance of 6.6 km in the west and the second, 1.89 mGal high gravity anomaly at profile distance of 31.5 km in the east, are 2 striking features of the Forks Road gravity profile. The western high gravity anomaly is relatively broad, about 11 km wide. The eastern high gravity anomaly is narrower, about 7 km wide.

Gravity anomalies are caused by lateral density contrasts in the subsurface at various depths, from the near surface to the basement. The Bell Road gravity profile is located approximately 2 km south of Forks Road gravity profile. The 1.4 mGal high and 5 km wide gravity anomaly along the Bell Road gravity profile (Rainsford and Biswas 2018) was modelled with a deep and relatively higher density feature in the Grenville Basement associated with the Central Metasedimentary Belt Boundary Zone (CMBBZ) (Easton and Carter 1991). It is expected that the 1.86 mGal and 1.89 mGal high gravity anomalies along the western and eastern parts of the Forks Road gravity profile both will have similar deep sources consistent with the CMBBZ. Boreholes BH14 and BH23 are located along the Forks Road profile at profile distances of approximately 437 m (to the north) and 320 m (to the south), respectively. Information from continuously cored borehole logs (Burt 2020) for BH14, BH23 and other nearby boreholes and the 3-D Paleozoic geology model (Carter et al. 2019, 2021) will be used to constrain the shallower Quaternary and Paleozoic layers in the GM-SYS 2-D model for the Forks Road gravity profile.

OTHER ACTIVITIES

In 2022, 12 field assistants were trained in operating the magnetic susceptibility meter. Measurements of magnetic susceptibility are used to semi-quantitatively assess the concentration of magnetic minerals in outcrop. Prior to the beginning of the field season, the susceptibility meters were calibrated to OGS rock standards and their performance monitored by means of these OGS reference samples to ensure consistent data quality. The newly collected field project measurements will be added to compilations from previous years. Data from these compilations can facilitate magnetic modelling and improve the accuracy of magnetic interpretations.

Handheld gamma-ray spectrometers were used by geological field crews on 4 projects. As such, training on the proper use of the OGS spectrometers was offered to field assistants accompanying the field geologist

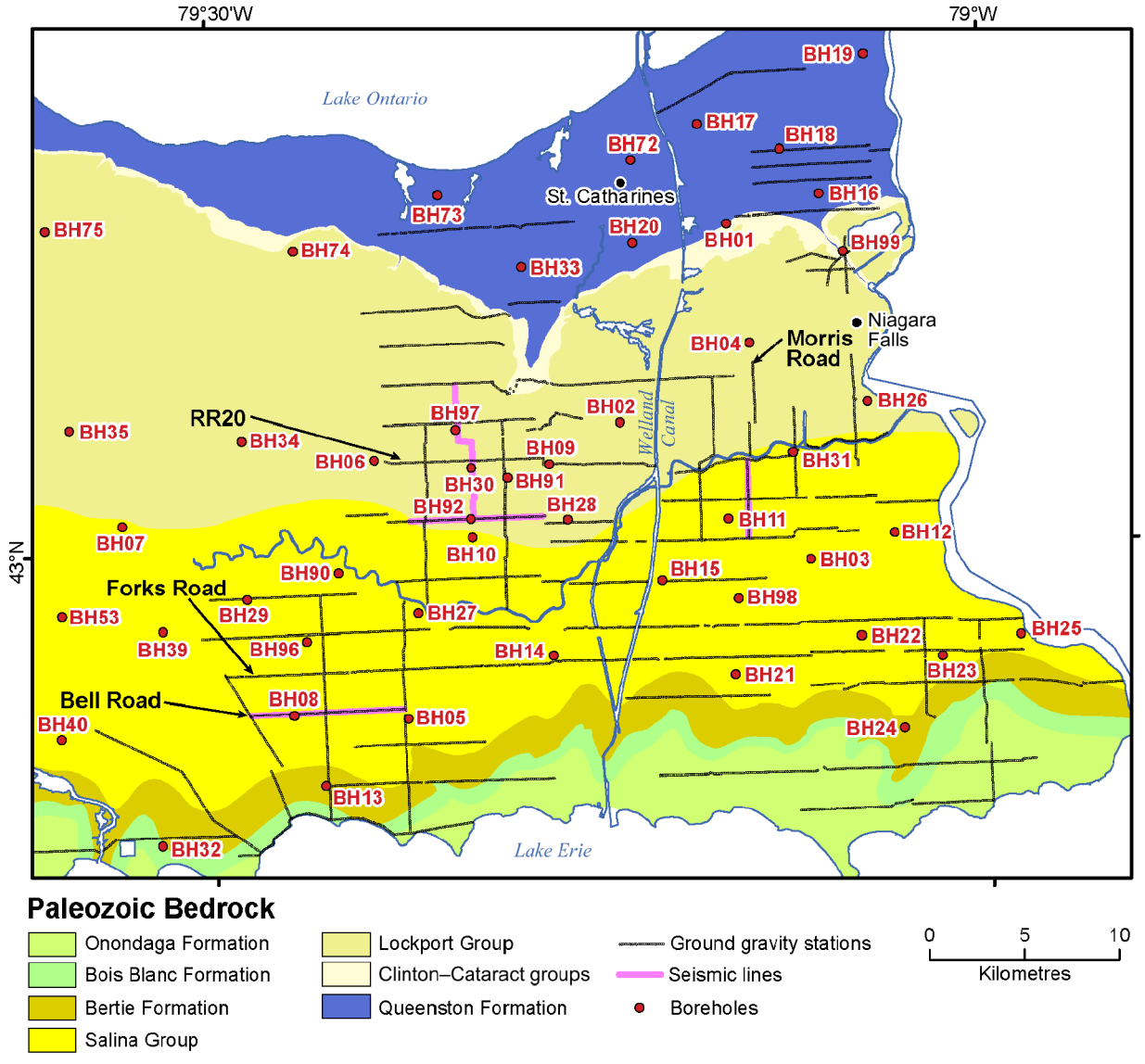


Figure 16.2. Location of the Niagara Peninsula 3-D sediment mapping project study area showing underlying Paleozoic bedrock (*modified from* Armstrong and Dodge 2007). The gravity stations for the east-trending Forks Road profile are indicated on the map. Note that the Forks Road profile is not accompanied by a seismic line. Profiles along Regional Road 20 (RR20), Morris Road and Bell Road were described by Rainsford and Biswas (2021), Rainsford, Biswas and Larsen (2020), Rainsford and Biswas (2018), respectively.

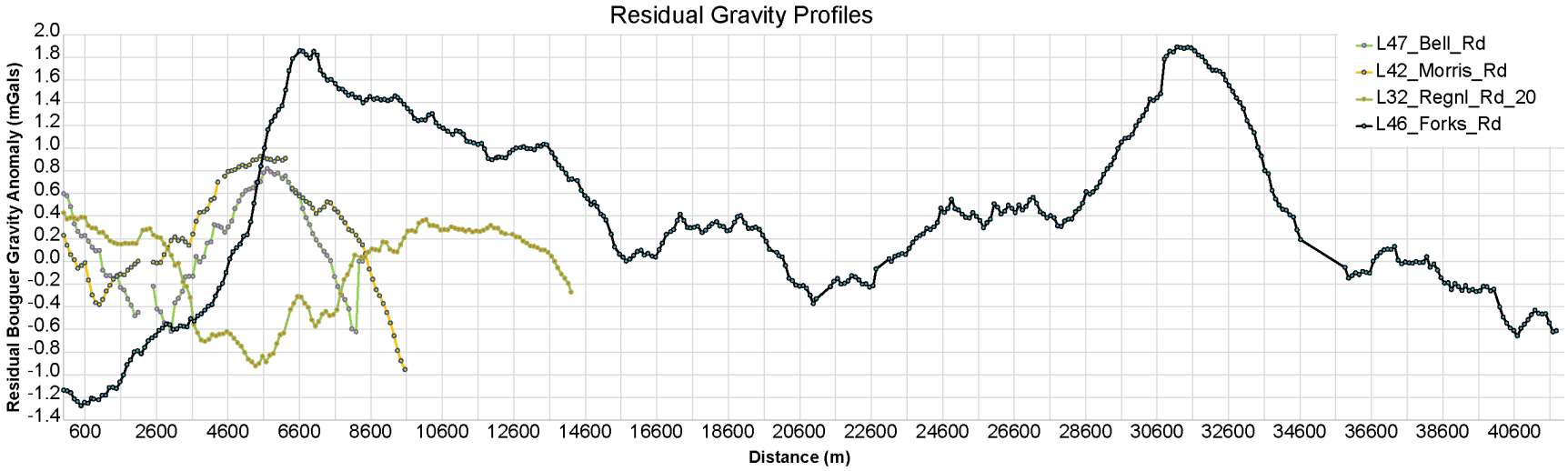


Figure 16.3. Residual Bouguer gravity anomalies along the 4 profiles in the study area marked on Figure 16.2. The 2 gravity high anomalies, one in the west and one to the east are distinctive features of the Forks Road profile. The Forks Road gravity anomalies are larger than the gravity anomalies along other 3 profiles in the study area. Multiple deep sources may be causing these high gravity anomalies along the Forks Road profile.

on their respective project. Radiometric readings are very useful in the field as they can distinguish between similar looking granitoids and locate radiogenic mineralization. The performance of these instruments is monitored annually for consistency at a convenient field location in Sudbury prior to field use.

The OGS continued to serve the public by addressing geophysical enquiries from clients in mineral exploration and by providing material support to other departments within the Ministry of Mines. One such example of the latter is the provision of training on the use of a gamma-ray spectrometer loaned to the Mine Rehabilitation group. This instrument will be used for a radiological study at the abandoned Lockerby Mine.

The availability of geophysical and other geoscience data collected by the OGS can be viewed geographically and downloaded using the OGSEarth application (www.mndm.gov.on.ca/en/mines-and-minerals/applications/ogsearth). The Geophysical Survey Index, found via the OGSEarth application, continues to be maintained and updated with each new release of geophysical data. The index can be downloaded as a KML file that can be viewed using Google Earth™ mapping service.

Free downloads of geophysical data are also available from the OGS online data warehouse—GeologyOntario (www.mndm.gov.on.ca/en/mines-and-minerals/applications/geologyontario). Hard-copy (paper) reports and maps, and physical media (CD or DVD) of digital data are also available for a nominal fee through the Publication Sales outlet:

Tel:	705-670-5691 (local)
Toll-free:	1-888-415-9845 ext. 5691 (Canada and United States)
Fax:	705-670-5770
E-mail:	pubsales.ndm@ontario.ca

REFERENCES

Armstrong, D.K. and Dodge, J.E.P. 2007. Paleozoic geology of southern Ontario; Ontario Geological Survey, Miscellaneous Release—Data 219.

Burt, A.K. 2013. The Niagara Peninsula study: A new three-dimensional Quaternary geology mapping project; *in* Summary of Field Work and Other Activities, 2013, Ontario Geological Survey, Open File Report 6290, p.38-1 to 38-21.

——— 2020. Results of the 2014–2017 drilling programs on the Niagara Peninsula: Graphic logs, descriptions and analytical data; Ontario Geological Survey, Miscellaneous Release—Data 383.

Carter, T.R., Brunton, F.R., Clark, J.K., Fortner, L., Freckelton, C., Logan, C.E., Russell, H.A.J., Somers, M., Sutherland, L. and Yeung, K.H. 2019. A three-dimensional geological model of the Paleozoic bedrock of southern Ontario; Ontario Geological Survey, Groundwater Resources Study 19 / Geological Survey of Canada, Open File 8618.

Carter, T.R., Logan, C.E., Clark, J.K., Russell, H.A.J., Brunton, F.R., Cachunjua, A., D'Arienzo, M., Freckelton, C., Rzyszczak, H., Sun, S. and Yeung, K.H. 2021. A three-dimensional geological model of the Paleozoic bedrock of southern Ontario, ed. v.2; Geological Survey of Canada, Open File 8795. doi.org/10.4095/328297

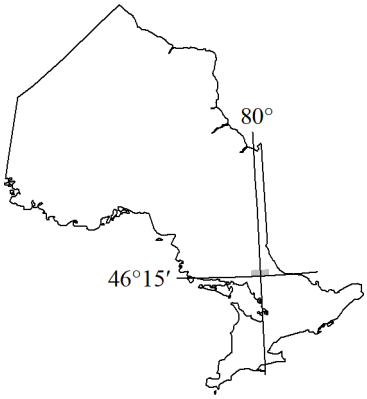
Easton, R.M. and Carter, T.R. 1991. Extension of Grenville basement beneath southwestern Ontario; Ontario Geological Survey, Open File Map 162, scale 1:1 013 760.

Rainsford, D.R.B. and Biswas, S. 2018. Summary of geophysical projects and activities; *in* Summary of Field Work and Other Activities, 2018, Ontario Geological Survey, Open File Report 6350, p.16-1 to 16-10.

——— 2021. Summary of geophysical projects and activities; *in* Summary of Field Work and Other Activities, 2021, Ontario Geological Survey, Open File Report 6380, p.14-1 to 14-9.

Rainsford, D.R.B., Biswas, S. and Larsen, T.O. 2020. Summary of geophysical projects and activities; *in* Summary of Field Work and Other Activities, 2020, Ontario Geological Survey, Open File Report 6370, p.11-1 to 11-10.

17. Project NE-22-004. Quaternary Geological Mapping of the Lake Nipissing Basin, Highway 17 Corridor, Northeastern Ontario



A.S. Marich[1]

[1]Earth Resources and Geoscience Mapping Section, Ontario Geological Survey

INTRODUCTION

This report outlines the initial findings from the first field season of a multi-year field program to update the Quaternary geology maps along the Highway 17 corridor between Sudbury and Mattawa, in northeastern Ontario. This area, despite being populated and along a main traffic route, lacks the 1:50 000 scale mapping typically used for land use planning, aggregate resource management, engineering studies and agricultural soils suitability mapping. Existing maps for the study area consist of a patchwork of regional maps by Boissonneau (1967, 1:508 680 scale); Harrison (1972, 1:125 000 scale) and several Northern Ontario Engineering and Terrain Studies (NOEGTS) that were completed at a scale of 1:100 000 and based on airphoto interpretation with limited field ground truthing (Gartner 1980a, 1980b, 1980c).

A new high-resolution digital terrain model (DTM) derived from lidar (light detection and ranging) remote sensing data for the Lake Nipissing, French River and Mattawa River watersheds has been acquired from the Ministry of Natural Resources and Forestry (2022). This DTM has approximately 10 cm vertical and horizonal resolution and shows the land surface without vegetation or anthropogenic features. The DTM allows delineation and mapping of landforms in greater detail than previously possible, as well as the identification of critical locations to collect field data in order to ground truth the DTM and produce detailed and accurate surficial maps. Field work during the summer of 2022 focussed on the areas between Hagar and Sturgeon Falls, represented by the National Topographic System (NTS) maps Verner (41 I/8) and Sturgeon Falls (31 L/5) (Figure 17.1A).

LOCATION AND PHYSIOGRAPHY

The study area for 2022 is more than 2000 km^2, about a quarter of which is occupied by Lake Nipissing (*see* Figure 17.1A). The landscape west of Lake Nipissing is dominated by low and flat-lying glacial lake plains with many small bedrock knobs. The bedrock knobs are commonly rounded and smoothed from glacial erosion and polishing and, in many cases, the bedrock is streamlined into linear ridges, with long axes oriented to the southwest, reflecting a combination of the structure of the bedrock and the direction of regional ice flow. Streamlined landforms include rock drumlins and roches moutonnées, as well as features exhibiting a steep up ice (stoss) side and gently sloping down-ice (lee) side. Another major feature of the study area is the east-trending Veuve River valley, which is parallel to Highway 17 between Hagar and just east of Verner (Figure 17.1B). River terraces are visible north and south of the highway, and this drainage route records water level changes in the Lake Nipissing basin spanning from the last deglaciation until the present.

Summary of Field Work and Other Activities, 2022,
Ontario Geological Survey, Open File Report 6390, p.17-1 to 17-9.

© King's Printer for Ontario, 2022

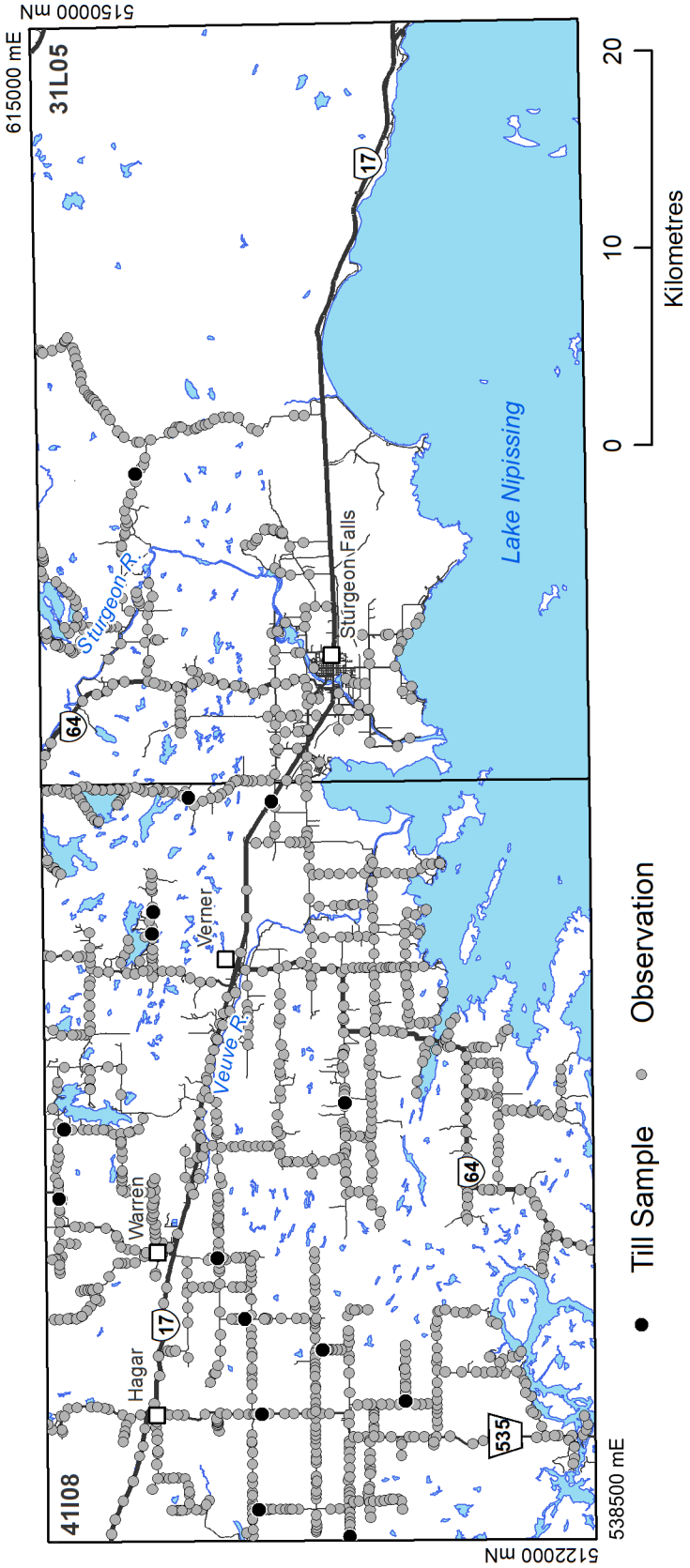


Figure 17.1. A) Study area with field observations and till sample locations. Observations follow transportation routes, and forest resource roads.

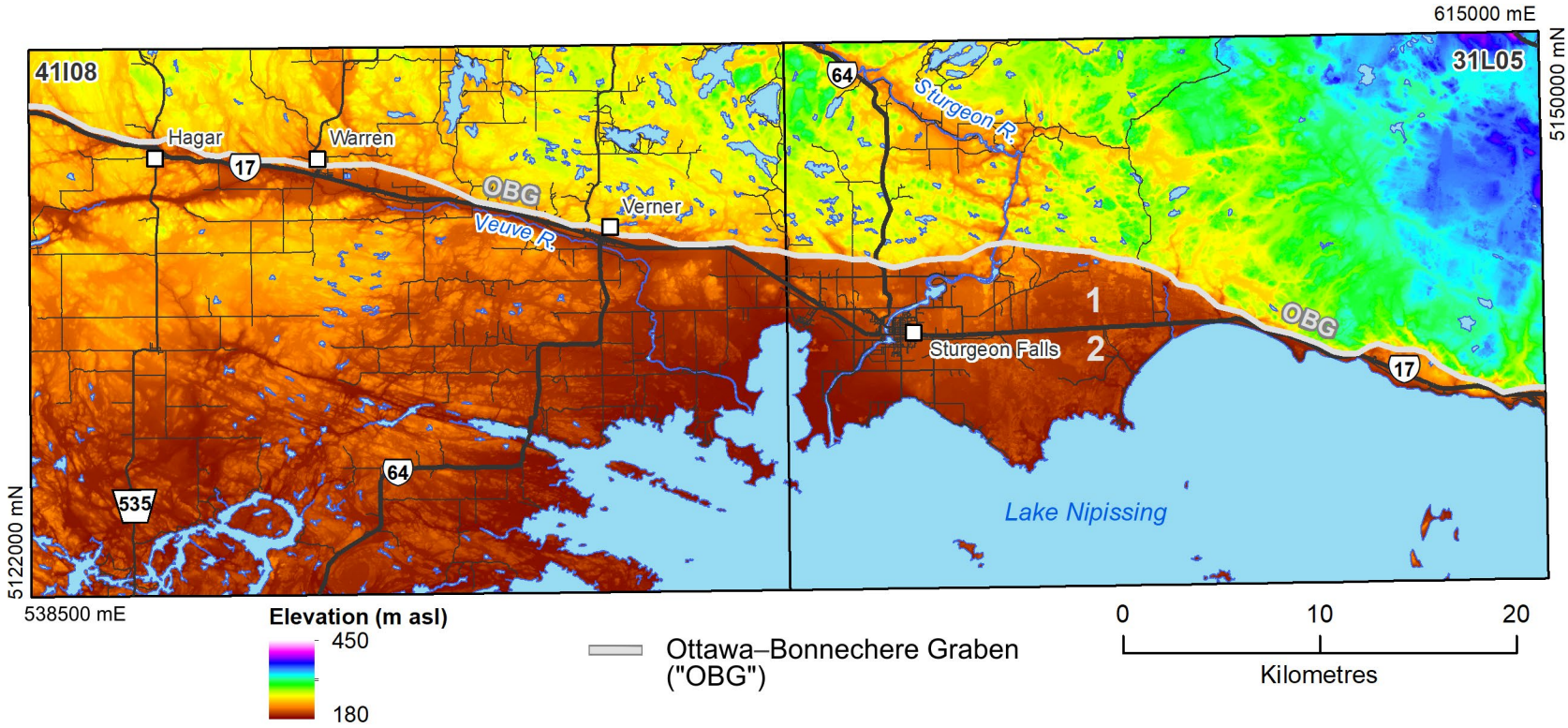


Figure 17.1. B) Digital terrain model (hillshade image) of the study area (data *from* Ministry of Natural Resources and Forestry 2022). The northern boundary of the Ottawa–Bonnechere Graben (OBG) is indicated by the pale grey line. Locations indicated by numbers on figure: 1) general location of the delta at Sturgeon Falls, and 2) location of shoreline features discussed in the text.

The area around and east of Sturgeon Falls is extremely flat, and a series of ancestral glacial lake shorelines are present (*see* "1" on Figure 17.1B). These are very subtle features that mark the various water-plane elevations of waterbodies in the Lake Nipissing basin.

A major bedrock structural feature influencing the modern landscape is the Ottawa–Bonnechere Graben (*see* Figure 17.1B). The northern boundary of the graben extends from the Hagar to Mattawa. The graben has been a strong influence on the surface drainage and glacial ice flow. North of the graben, the landscape is predominantly bedrock, whereas, to the south, bedrock occurs as streamlined landforms separated by flat-lying terrain.

METHODS

Field work was conducted between May and August of 2022, with 1400 observations of sediments, landforms and ice-flow indicators. In addition, 16 C-horizon till samples were collected. Sampling occurred along roads and forestry resource roads and trails accessed via truck or by foot. Samples were obtained from hand dug pits (up to 1 m deep), road cuts, roadside ditches, stream cut banks and excavations. Sampling density is irregular because till was rarely observed at surface, but was commonly found in the lee of bedrock knobs and buried in the areas between bedrock knobs by glacial lake sediments. Samples were screened in the field to remove the +5 mm fraction and screened material will be used for pebble lithology counts. At each sample site, 2 samples of C-horizon till were collected: 1) a 10 kg sample for heavy mineral concentration and recovery of gold grains, kimberlite indicator minerals (KIM) and metamorphic/magmatic massive sulphide indicator minerals (MMSIM®[2]) and 2) a 2 to 3 kg sample for −63 µm fraction geochemical analysis and determination. The sampling procedures follow standard protocols used by the Ontario Geological Survey (e.g., Bajc 1999).

BEDROCK GEOLOGY

The study area is located within the Central Gneiss Belt of the Grenville Province. These rocks are highly metamorphosed and range in age from about 1.2 to 2.7 billion years old (Figure 17.2) (Ontario Geological Survey 2011).

The most common rocks in the study area are layered biotite gneisses and migmatites. These rocks occur in an upland along the northern boundary of the Ottawa–Bonnechere Graben and as isolated bedrock knobs west of Lake Nipissing.

Felsic igneous rocks, typically gneissic, were derived from tonalite, granodiorite, monzonite, granite and/or syenite intrusions, and are dominant in the southern part of the study area and underlie Lake Nipissing (Ontario Geological Survey 2011).

Anorthosite and related igneous rocks, also typically gneissic, consisting of anorthositic gabbro, gabbro and related gneisses, crop out in a northwest-trending band in the western part of the study area south of Hagar near the community of St. Charles.

Mafic rocks occur in small pockets in the western half of the study area (within the area represented by the Verner NTS map). These rocks include amphibolite, gabbro, diorite and mafic gneisses.

Several carbonatite and/or alkalic complexes occur as islands in Lake Nipissing (Ontario Geological Survey 2011). In addition, local outliers of Ordovician carbonate rocks are also exposed on islands in Lake Nipissing.

[2] *MMSIM is a registered trademark of Overburden Drilling Management Limited, Nepean, Ontario.*

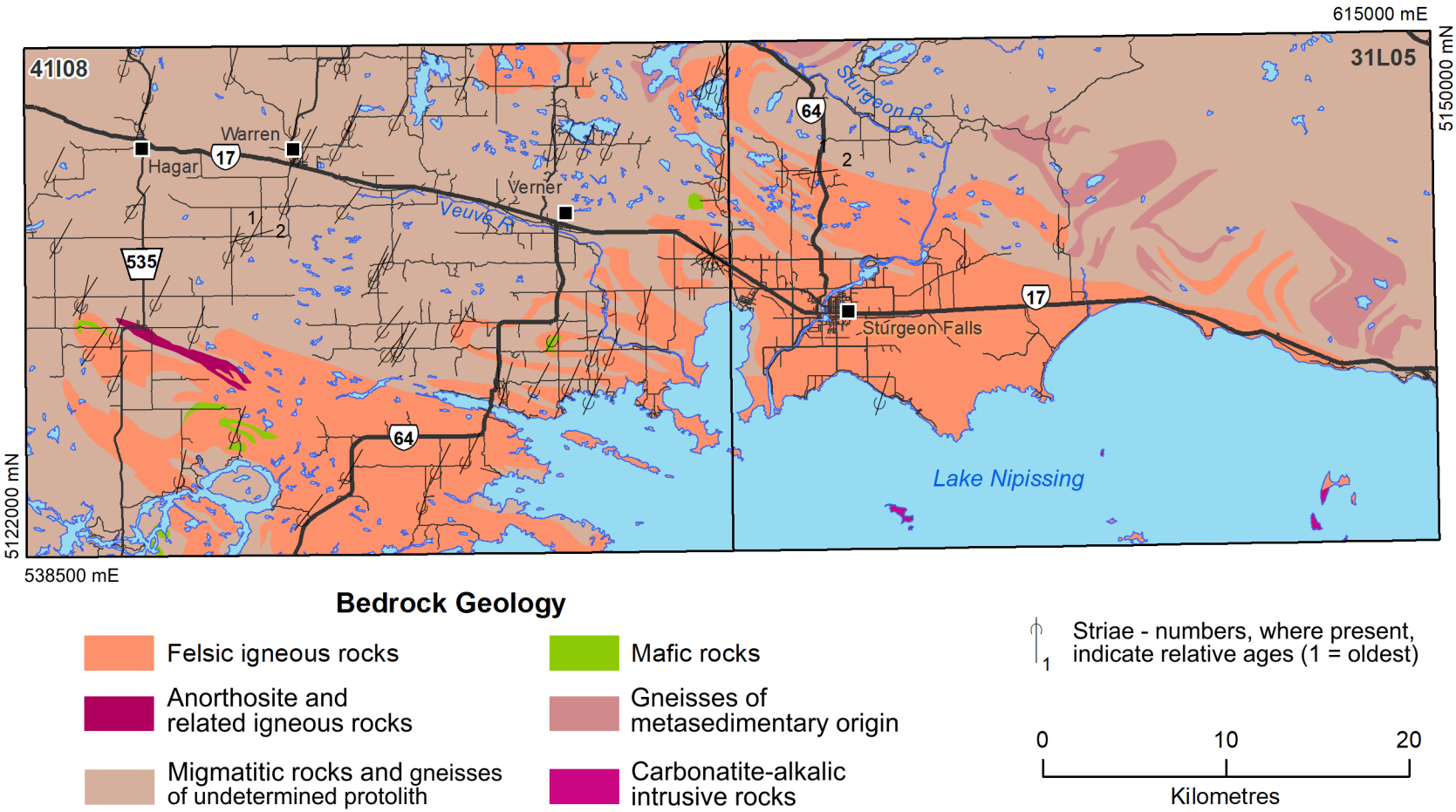


Figure 17.2. Simplified bedrock geology (*modified from* Ontario Geological Survey 2011) of the study area, including striae measurements collected during the summer of 2022.

QUATERNARY GEOLOGY

Ontario's landscape has been affected by multiple glaciations, the most recent being the Wisconsinan glaciation. The study area was mostly deglaciated after 12 100 (calibrated) radiocarbon years before present (Dalton et al. 2020). Glaciers erode bedrock and deposit sediments, changing the surficial drainage and geomorphology of the landscape. The Lake Nipissing basin was a large control on the development of the landscape and, up until recently (~12 100 years ago), ancestral Lake Nipissing and its predecessor glacial Lake Algonquin occupied much more of the study area (Boissonneau 1968).

Part of this project is aimed at understanding the genesis of landforms and their associated sediments to further understand events during deglaciation which are responsible for today's landscape. The following section introduces some landforms and sediment types identified in the field.

The regional till is the oldest sedimentary unit observed in the study area. The till is a silty sand diamicton, with varying silt content (Photo 17.1A). Clasts consist of mixed Precambrian lithologies, with less than 5% to about 10% clasts. Clasts are commonly bullet shaped, faceted and striated, and are disintegrating *in situ*. The till matrix varies in consolidation and, in some cases, is very fissile. Exposures of till are commonly confined to uplands and the lees of bedrock highs where it often makes up the tail portion of crag and tails with long axes oriented northeast-to-southwest. The crag-and-tail features are commonly 100 m wide and several hundred metres long.

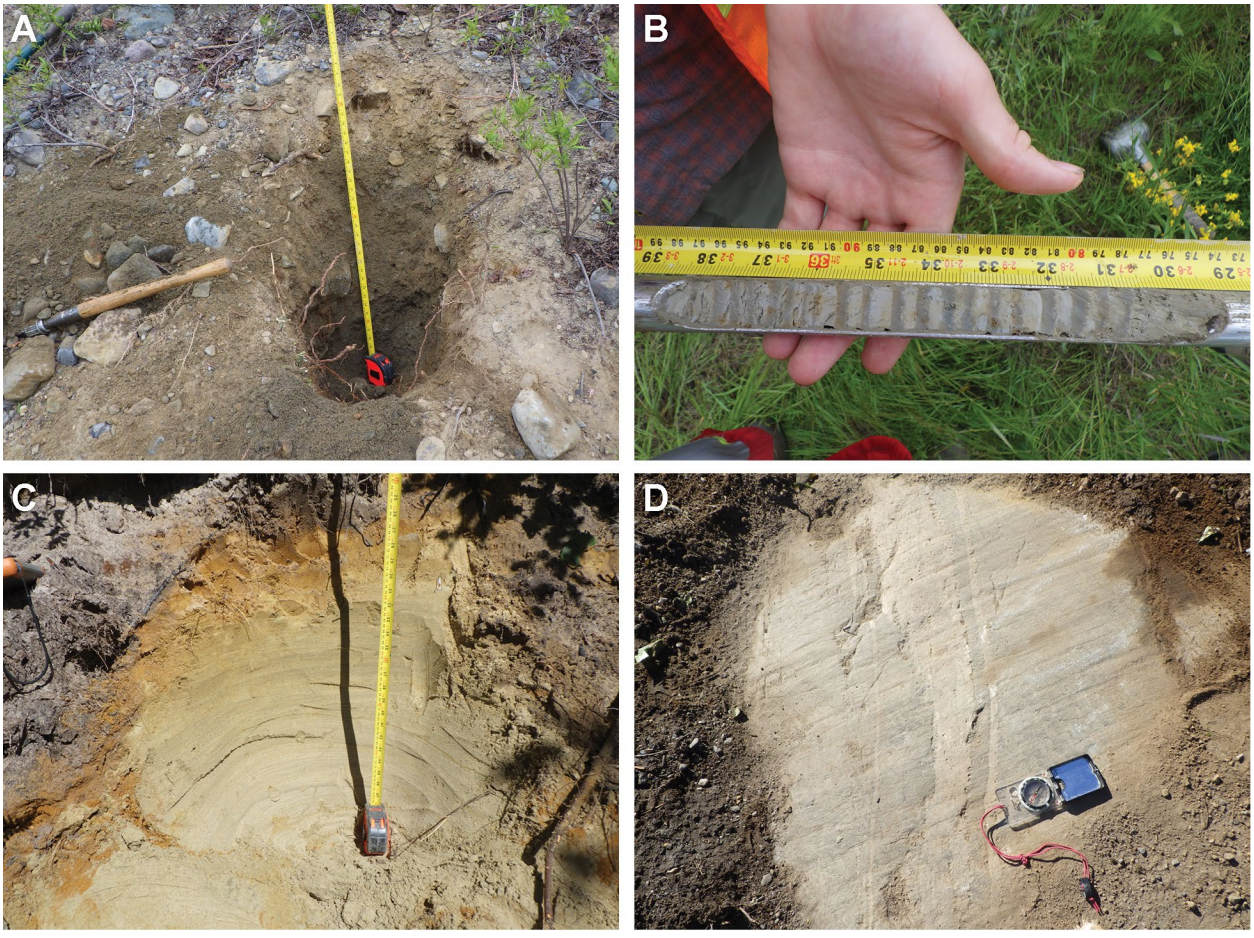


Photo 17.1. Photographs of **A**) silty sand diamicton (till); **B**) varves (dark grey laminae are clay (winter deposition), light grey laminae are silt (summer deposition); **C**) typical horizontally laminated fine- to medium-textured sand observed in dunes; and **D**) glacial striae; ice flow is from bottom left corner to top right corner of photograph (southwestward); compass is 17 cm long.

In addition, till was observed in De Geer moraines. These moraines are thin (<5 m wide), only approximately 1 to 2 m high, and up to several hundred metres long, but are most commonly tens of metres long. De Geer moraines form subaqueously at the ice margin and may mark yearly stillstands of a retreating glacier (e.g., Lindén and Möller 2005; Bouvier, Johnson, and Påsse 2015). The De Geer moraines observed in the study area are composed of stony sediment similar to the till described above, but without the fine-textured component of the matrix. Work on these ridges is ongoing, but the current interpretation of these sediments is that the moraine ridges were deposited and subsequently reworked by shoreline processes, "washing" away the fine-textured sediments, leaving a stonier material. In some examples, the sediment is so clast rich, it appears to be open-work gravel.

A strong understanding of the underlying bedrock geology is helpful in understanding the landscape, till provenance and till geochemistry. It is important to understand if sediments are composed of local or far-travelled lithologies because those observations can aid in reconstructing past ice-flow events (e.g., tracing materials to their source up ice).

Glaciofluvial ice-contact sands and gravels are commonly observed as part of eskers within the study area. The eskers are small systems of sinuous ridges that have undulating surfaces ranging from 5 to 15 m above surrounding terrain, are greater than 150 m wide, and can be several hundred metres to 1 or 2 km in length. The esker ridges are oriented to the south or southwestward. Exposures within these ridges show varying sand and gravel content and range in thickness from a few metres to more than 10 or 15 m. Some sections are dominated by sands with minor beds of fine to coarse cobbles and boulder gravel, whereas others are gravel dominant, clast supported (or openwork) with clasts commonly 5 to 10 cm in diameter, but ranging up to 2 m in diameter. Sedimentary structures observed in these ice-contact deposits include horizontal bedding, and ripple and cross-bedded sands that are consistent with sediments deposited by flowing water and are consistent with esker crest orientation. Of the exposures visited, most contained clasts of local Grenville Province rocks, with rarer far-travelled clasts of the Gowganda Formation of the Southern Province originating several tens of kilometres north of the study area.

The Verner and Sturgeon Falls study area are dominated by bedrock and glaciolacustrine deposits. The glacial lake sediments occupy lowlands, creating a very flat land surface, often with very poor drainage. These sediments are predominantly deep-water deposits of silt and clay. Thickness of these sediments can vary from a few centimetres to several metres, although no exposures have shown the lower contact of these deposits. Much of the deep-water sediments are rhythmically bedded, likely varves showing seasonal deposition of silt (summer) and clay (winter) (Photo 17.1B). These sediment couplets represent deposition of clay in very calm conditions occurring when the lake was ice covered, and silt or coarser sediments deposited during ice-free conditions and when meltwater flows were more abundant. Individual couplets vary in thickness from a few millimetres up to 10 cm. The variations in thickness of the couplets are the result of multiple factors including the amount of sediment input into the proglacial lake, and the duration of ice-free and ice-covered periods. Varved fine-textured glaciolacustrine sediments occur most commonly in the low-lying areas just west of Lake Nipissing, but they have also been observed elsewhere, intermittently throughout the study area.

Nearshore glaciolacustrine deposits consisting of silty very fine- to fine-textured sands, sometimes interbedded with silts and clay, were also observed in the study area. These deposits also vary in thickness, but the maximum depth was not observed in section or in soil probe observations. Landforms associated with these deposits include glacial lake beach ridges (most predominantly east of Sturgeon Falls (230 m above sea level (asl)) (*see* "2" on Figure 17.1B), a spit at Warren (225–230 m asl), and a large delta in the vicinity of the Sturgeon Falls waste disposal site (220 m asl) (*see* "1" on Figure 17.1B). The shoreline features consist of very low-relief beach ridges composed of fine- to medium-fine–textured sands. The beach ridges are easily identified on the lidar DTM, but can be very difficult to observe on the land surface. These ridges mark successive lowering of past glacial lake levels and levels of modern Lake

Nipissing. Future work will include sampling sands within these ridges for geochronological analysis by optically stimulated luminescence to improve the constraint on the timing of deglacial events within the Lake Nipissing basin. The spit located in the town of Warren is the result of longshore processes where beach sands migrated westward connecting an isolated bedrock knob to the main beach. The delta at Sturgeon Falls is a broad and flat sand plain, which has been dissected by the modern Sturgeon River and its tributaries. This feature was developed by meltwater drainage through the Sturgeon River valley, which led to sand and gravel deposition along the shorelines of glacial Lake Algonquin and, later, the Nipissing Phase of the upper Great Lakes. During deglaciation, as a result of isostatic uplift and changing outlets, lake levels in glacial Lake Algonquin dropped, exposing the delta and beach ridge sands which dried and were later reworked by wind creating a cluster of sand dunes on the surface of the delta. These dunes are small, generally less than 5 m high, and are commonly poorly developed. Sands in these dunes are horizontally laminated and exhibit minor heavy mineral laminations (Photo 17.1C). Of note is a prominent shoreline ridge, along the east side of the delta, which is occupied by a row of dunes.

The youngest deposits within the study area are modern alluvium consisting of organic rich silts to sands, commonly within the active floodplain of rivers, and organic deposits (peat and muck) within wetlands that occur throughout the study area along river systems and within poorly drained low-lying areas.

Numerous paleoflow measurements were made: 66 measurements were plotted within ESRI® ArcGIS® in order to ascertain regional ice-flow patterns (*see* Figure 17.2). Some of these indicators are recorded directly on the bedrock surface, including striae, chattermarks, grooves and plucked lee surfaces (e.g., Photo 17.1D). Much of the bedrock surface in the study area is highly weathered, has undergone many freeze–thaw cycles, thereby removing any indication of ice-flow direction. Striae are most well preserved on fine-textured lithologies and are often easily identified on quartz veins because quartz is more resistant to erosion. Larger scale ice-flow indicators include landforms, such as streamlined bedrock forms (roches moutonées, drumlins and crag and tails), were observed on the land surface and interpreted from the lidar DTM. Collectively, these features indicate ice flow in the study area was dominated by a southwestward flow with some southward-flow indicators, mostly in the Sturgeon Falls study area. Several crosscutting striae sites show a possible older flow trending southwest to west. Ongoing work will determine the relative chronology indicated by these ice-flow indicators.

FUTURE WORK

Mapping of landforms from the lidar DTM is ongoing, and additional field work is planned for 2023 and 2024. Future field work will focus on the area from North Bay to Mattawa.

ACKNOWLEDGMENTS

The author would like to acknowledge the field assistance of Grant Hagedorn, Hunter Rusk, Jeremy Creppin, Ben Gaudet and Laura Handley, without whom the summer's field work would not have been a success. Additional thanks go to Ontario Geology Survey (OGS) staff Riley Mulligan, Michael Easton, and Shirley Péloquin, as well as Jennifer Organ (Newfoundland and Labrador Geological Survey), for ongoing discussions of both Quaternary and Precambrian geology relevant to the study area.

The author would like to thank the Algonquins of Pikwakanagan First Nation, Dokis First Nation, Nipissing First Nation, Henvey Inlet First Nation, Wolf Lake First Nation, Eagle Village First Nation, MNO Mattawa Métis Council and MNO Ottawa Métis Council for allowing the Ontario Geological Survey to map their traditional land use area.

Thorough and insightful reviews of this manuscript were completed by Grant Hagedorn and Riley Mulligan and are greatly appreciated.

REFERENCES

Bajc, A.F. 1999. Results of regional humus and till sampling in the eastern part of the Shebandowan greenstone belt, northwestern Ontario; Ontario Geological Survey, Open File Report 5993, 85p.

Boissonneau, A.N. 1967. Algoma, Sudbury, Timiskaming and Nipissing, surficial geology; Ontario Department of Lands and Forests, Map S465, scale 1:506 880.

——— 1968. Glacial history of northeastern Ontario II. The Timiskaming–Algoma area; Canadian Journal of Earth Sciences, v.5, p.97-109.

Bouvier, V., Johnson, M.D. and Påsse, T. 2015. Distribution, genesis and annual-origin of De Geer moraines in Sweden: Insights revealed by LiDAR; GFF [formerly Geologiska Föreningens i Stockholm Förhandlingar], v.137, p.319-333.

Dalton, A.S., Margold, M., Stokes, C.R., Tarasov, L., Dyke, A.S., Adams, R.S., Allard, S., Arends, H.E., Atkinson, N., Attig, J.W., Barnett, P.J., Barnett, R.L., Batterson, M., Bernatchez, P., Borns, H.W., Breckenridge, A., Briner, J.P., Brouard, E., Campbell, J.E., Carlson, A.E., Clague, J.J., Curry, B.B., Daigneault, R-A., Dube-Loubert, H., Easterbrook, D.J., Franzi, D.A., Friedrich, H.G., Funder, S., Gauthier, M.S., Gowan, A.S., Harris, K.L., Hétu, B., Hooyer, T.S., Jennings, C.E., Johnson, M.D., Kehew, A.E., Kelley, S.E., Kerr, D., King, E.L., Kjeldsen, K.K., Knaeble, A.R., Lajeunesse, P., Lakeman, T.R., Lamothe, M., Larson, P., Lavoie, M., Loope, H.M., Lowell, T.V., Lusardi, B.A., Manz, L., McMartin, I., Nixon, C., Occhietti, S., Parkhill, M.A., Piper, D.J.W., Pronk, A.G., Richard, P.J.H., Ridge, J.C., Ross, M., Roy, M., Seaman, A., Shaw, J., Stea, R.R., Teller, J.T., Thompson, W.B., Thorleifson, L.H., Utting, D.J., Veillette, J.J., Ward, B.C., Weddle, T.K. and Wright, H.E. 2020. An updated radiocarbon-based ice margin chronology for the last deglaciation of the North American Ice Sheet Complex; Quaternary Science Reviews, v.234, paper 106223. doi.org/10.1016/j.quascirev.2020.106223

Gartner, J.F. 1980a. Cartier area (NTS 41I/NW), districts of Algoma and Sudbury; Ontario Geological Survey, Northern Ontario Engineering Geology Terrain Study 94, 18p. Accompanied by Maps 5000 and 5004, scale 1:100 000.

——— 1980b. Capreol area (NTS 41I/NE), districts of Nipissing and Sudbury; Ontario Geological Survey, Northern Ontario Engineering Geology Terrain Study 95, 16 p. Accompanied by Map 5001, scale 1:100 000.

——— 1980c. North Bay area (NTS 31L/SW), districts of Nipissing and Parry Sound; Ontario Geological Survey, Northern Ontario Engineering Geology Terrain Study 101, 19p.

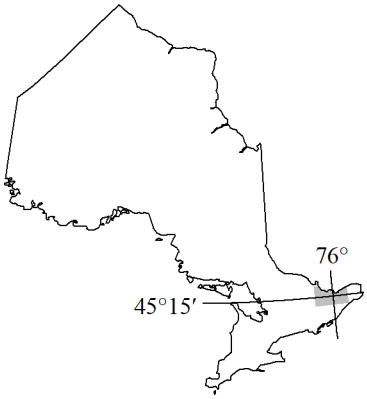
Harrison, H.E. 1972. Quaternary geology of the North Bay–Mattawa region, Ontario–Quebec; Geological Survey of Canada, Preliminary Map 3-1971, scale 1:125 000.

Lindén, M., and Möller, P. 2005. Marginal formation of De Geer moraines and their implications to the dynamics of grounding-line recession; Journal of Quaternary Science, v.20, p.113-133.

Ministry of Natural Resources and Forestry 2022. Ontario digital terrain model (Lidar-derived) - Lake Nipissing 2020 DTM; Ministry of Natural Resources and Forestry, Provincial Mapping Unit, Peterborough, Ontario, available on Ontario GeoHub.

Ontario Geological Survey 2011. 1:250 000 scale bedrock geology of Ontario; Ontario Geological Survey, Miscellaneous Release—Data 126 – Revision 1.

18. Project SO-19-003. Sediment Mapping in the City of Ottawa, Southeastern Ontario



R.P.M. Mulligan[1]

[1]Earth Resources and Geoscience Mapping Section, Ontario Geological Survey

INTRODUCTION

Field work in the Ottawa area was completed in late August 2022. The purpose of the work was to develop an improved understanding of regional sediment landform distribution, physical properties and genesis through the investigation of large cutbanks along rivers and streams that expose thick sequences of Quaternary sediments. The primary goal of field work in 2022 was to develop a more thorough understanding of marine clays, which, in some areas, pose a potential risk for failure and initiation of retrogressive landslides (Brooks and Adams 2020). This report briefly outlines some of the activities and findings of this year's field work, improves the description of landform distribution and genesis in the area based on new terrain data, and summarizes the preliminary geochronology results and ongoing work with samples collected in 2019 (Mulligan 2019).

REGIONAL GEOLOGICAL SETTING

The City of Ottawa lies within the Ottawa–Bonnechere Graben, a heavily faulted rift valley that cuts through rocks of the Proterozoic Grenville Province, and separates 2 physiographic regions: the Laurentian Highlands to the north in Quebec and the Algonquin highlands to the west. Several inliers of Precambrian rocks crop out in the northwestern part of the city, which is a result of differential downfaulting that began in the early Cambrian and because of subsequent preferential erosion of adjacent younger Paleozoic strata. Most of the City is underlain by Cambrian and Ordovician clastic and carbonate rocks, which are currently the focus of a multi-year mapping project (Béland Otis, this volume). Carbonate rocks within the Ottawa Valley have locally been dissolved to form a variety of karst features, which increase the overall rates of groundwater recharge, flow, potential contaminant transport, and locally create conditions that could introduce public safety hazards (Brunton 2013, 2019; Brunton and Brintnell 2020). Quaternary sediments in the region were, with few exceptions, deposited during the Late Wisconsin (<30 000 years) and form successions that are commonly 10 to 30 m thick, but rarely exceed 100 m in the deepest bedrock valleys.

2022 FIELD RESULTS

Several deep river exposures were visited in 2022 to analyze grain size and geochemistry of clay deposits in advance of potential future drilling programs. Four outcrops were selected for clay geochemistry profiles in the City of Ottawa, based on their geographic locations, proximity to recent landslides or major changes in bedrock geology, and thickness of exposed strata (Figure 18.1A: blue

Summary of Field Work and Other Activities, 2022,
Ontario Geological Survey, Open File Report 6390, p.18-1 to 18-7.

© King's Printer for Ontario, 2022

stars). An additional location was sampled northwest of Ottawa in the Town of Renfrew (*see* Figure 18.1A). Marine clays were sampled at intervals of 0.25 to 0.5 m along a vertical profile at each site, with the sampling interval shortened to 0.10 m within, and in proximity to, the underlying rhythmite facies. Samples have been submitted for geochemistry analysis to build a baseline understanding of geochemical trends in the clays and compare with previously published studies from cored boreholes in the region (Medioli et al. 2012).

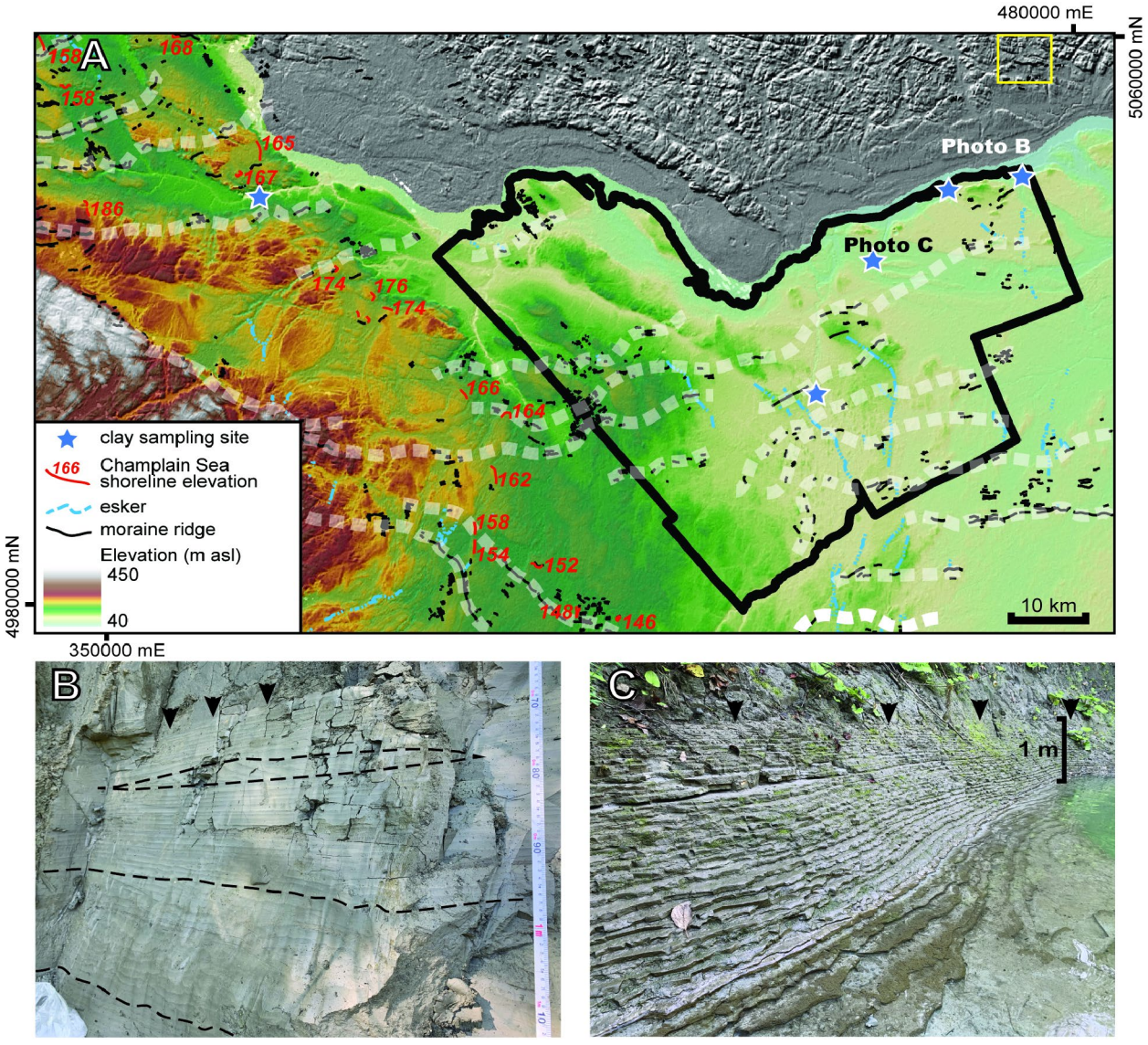


Figure 18.1. A) City of Ottawa (thick black outline) and select glacial landforms overlain on regional digital elevation model (DEM) and hillshade (Ministry of Natural Resources and Forestry 2012); Quebec hillshade is *from* Ministère des Forêts, de la faune et des parcs (2016). Prominent Champlain Sea shorelines are shown in red, with elevations reported in metres above sea level. Semi-transparent dashed white lines denote likely correlation of moraine ridges (thin black lines). Blue stars show locations of clay sample profiles collected in 2022. Locations of photos shown in **B** and **C** are labelled on the map. Yellow box shows location of shoreline features at 230 m asl identified on lidar data (Quebec) that may represent northern extensions of glacial Lake Candona, a precursor to the Champlain Sea. Data are projected using North American Datum 1983 (NAD83) Universal Transverse Mercator (UTM) in Zone 18N. **B)** and **C)** Exposures of thinly bedded glaciolacustrine(?) rhythmites overlain by massive to crudely stratified and fossiliferous marine mud (contact denoted with black arrows). Black dashed lines in **B)** denote zones of disturbed bedding.

Table 18.1. Radiocarbon age and morphostratigraphic context of marine shells sampled in 2019. Note that radiocarbon ages have not been calibrated.

Submitter ID	Lab ID	Material	Deposit and Elevation [1]	^{14}C age years BP [2]	$F^{14}C$ [3]
2019-OT-S02a	UOC-11566	Shell (*Hiatella*)	Beach; 86 m asl	10 935 ± 31	0.2563 ± 0.001
2019-OT-S02b	UOC-11567	Shell (*Hiatella*)	Beach; 86 m asl	10 817 ± 30	0.2601 ± 0.001
2019-OT-S13a	UOC-11568	Shell (*Macoma*)	Fluvial; 83 m asl	10 957 ± 33	0.2556 ± 0.001
2019-OT-S13b	UOC-11569	Shell (*Macoma*)	Fluvial; 83 m asl	11 056 ± 32	0.2525 ± 0.001
2019-OT-S21a	UOC-11570	Shell (*Macoma*)	Beach; 110 m asl	11 178 ± 32	0.2487 ± 0.001
2019-OT-S21b	UOC-11571	Shell (*Macoma*)	Beach; 110 m asl	11 158 ± 33	0.2493 ± 0.001
2019-OT-S22a	UOC-11572	Shell (*Macoma*)	Beach; 100 m asl	11 488 ± 31	0.2393 ± 0.0009
2019-OT-S22b	UOC-11573	Shell (*Macoma*)	Beach; 100 m asl	10 926 ± 34	0.2566 ± 0.0011
2019-OT-S46a	UOC-11574	Shell (*Macoma*)	Beach; 108 m asl	11 192 ± 34	0.2483 ± 0.001
2019-OT-S46b	UOC-11575	Shell (*Macoma*)	Beach; 108 m asl	11 127 ± 31	0.2503 ± 0.001

[1] Elevation values in metres above sea level.
[2] Radiocarbon years BP = before present (1950).
[3] Fraction modern carbon is calculated as the ratio of the sample $^{14}C/^{12}C$ ratio to the standard $^{14}C/^{12}C$ ratio.

Till and glaciofluvial sediments that underlie clay deposits were observed at several locations along the Rideau River, Green's Creek and Beckett's Creek. A silty sand till was observed along the base of several sections. As noted at many locations in the region, the matrix colour and dominant clast lithologies bear many similarities to local bedrock. Along Green's Creek, in a section that cuts through black shale of the Upper Ordovician Billings Formation (Béland Otis, this volume) the lowermost 1.5 m of till was dark grey and contained monolithic angular black shale clasts. Farther upsection, a wider variety of carbonate clasts were observed, with rare occurrences of crystalline rocks derived from the Laurentian Highlands in Quebec. Till samples were taken at several locations to fill gaps left from the 2019 sampling and to build vertical profiles through the surficial till where possible and to develop a baseline to compare with previous results from the region (e.g., Kettles and Shilts 1989) and potentially improve understanding of ice-flow history in the area.

At multiple exposures, horizontal to planar cross-bedded sand to pebble gravel were observed overlying till or bedrock. Sediments commonly fine upward into interstratified fine-grained sand and silt, with ripple- and dune-scale cross-laminations indicating paleoflows to the south and southeast. Bed contacts are commonly deformed into ball-and-pillow structures recording syndepositional dewatering. These sediments are typical of subaqueous fans deposited during ice retreat in the region and are sharply overlain by the clays that were the focus of this year's field work.

GEOCHRONOLOGY RESULTS

In 2019, 10 samples of marine bivalve shells were submitted for radiocarbon age determination at the André E. Lalonde Accelerator Mass Spectrometry Laboratory, the University of Ottawa. The 10 samples were all from well-preserved, articulated marine bivalves—2 *Hiatella arctica* and 8 *Macoma baltica*—extracted from nearshore and fluvial sediments at a range of elevations at 5 sites, recording relative sea level fall during deglaciation. Duplicate samples were obtained from each site, along the same horizon and are designated with a suffix "a" or "b" at the end of the sample number (Table 18.1). Four of 5 duplicate sets returned ages that deviated by 20 to 118 ^{14}C years (samples 2019-OT-S22a and -22b were 562 ^{14}C years apart, which may indicate that at least 1 these 2 samples had been reworked and, therefore, are less reliable).

Shell material from marine organisms contains primarily carbonate from the surrounding water and commonly incorporates material from older carbon derived from old calcareous sediments and bedrock,

such as the Paleozoic carbonate bedrock in this region, leading to the overestimation of ages. A reservoir correction factor needs to be applied to the radiocarbon age to account for the marine reservoir effect to reflect the true age of the organism. The geological setting of the Champlain Sea creates numerous problems for assigning a reliable reservoir correction as the water body underwent numerous rapid changes in salinity, stratification, sediment provenance and experienced changes in the duration of sea ice cover, complicating the assignment of a useful reservoir correction factor. Assessing whether a correction factor can be applied to these radiocarbon dates is ongoing, but the reader should note that the radiocarbon ages presented here have not been calibrated to calendar years.

In addition, 10 sand samples were also submitted for age determination by optically stimulated luminescence at Utah State University Luminescence Laboratory. The intent was to use luminescence ages from sands deposited along shoreline of the Champlain Sea or from sand plains exposed immediately after its drainage to constrain the water level history. This, in turn, would help improve the understanding of water depth changes through time, allowing for better assignment of reservoir correction of radiocarbon ages of marine shells in the region. Final results of the optically stimulated luminescence analyses will be provided in a subsequent report after additional samples have been collected and studied. As such, they are not discussed here.

REGIONAL GEOLOGICAL HISTORY

Glacial striae and subglacial bedforms indicate both local- and regional-scale changes in ice-flow directions throughout the last glacial. At least 3 major phases of ice advance are recorded in the area, with the oldest advancing southward, followed by predominantly southwest flow, then south to southeast flow during deglaciation (e.g., Ross et al. 2006). The middle phase of southwest ice flow likely relates to the onset of ice streaming in the Great Lakes sector of the southern Laurentide Ice Sheet during deglaciation, between 17 and 12.5 calibrated (cal) kyr BP (Margold, Stokes and Clark 2018) and the possible connection between this phase of fast ice flow with rapid calving associated with shutdown of the Laurentian Trough Ice stream along Canada's Atlantic coast should be investigated.

Several local areas show evidence of very late phases of ice flow. One area west of the Rideau River is of particular interest, because there is a cluster of low-relief east-southeast–oriented drumlins that overprint older south-southwest–oriented streamlined forms. Southeast of this cluster of drumlins is a large subaqueous fan complex that was deposited where 2 esker systems converge. A genetic link between the late-stage drumlins and eskers appears likely; meltwater discharging from beneath the ice in this area affected the local ice surface profile, leading to the development of a calving bay and subsequent new ice gradient converging on the esker from the west, during which time the low-relief drumlins may have been formed. A similar setting in Sweden resulted in rapid drumlin formation during deglaciation (Dowling, Moller and Spagnolo 2016). Excellent examples of late-stage flow within the topographic confines of the Ottawa River valley occur between Renfrew and Petawawa, where multiple sets of subtle streamlined bedforms terminate at arcuate till-cored moraines (Barnett 1988; Mulligan, Eyles and Marich 2019; *see* Figure 18.1).

Several additional large esker systems preserved in the region (Cummings et al. 2011). Eskers typically follow the trend of bedrock valleys and the long axes of subglacial bedforms, indicating confinement of channelized meltwater systems beneath a grounded ice sheet, despite its restricted thickness during local deglaciation. Where subglacial meltwater reached the ice front, thick and broader accumulations of sand and gravel were deposited as subaqueous fans into proglacial water bodies (Rust 1988; Sharpe 1988).

Initially, a proglacial lake (Lake Candona–For Ann phase of glacial Lake Iroquois) ponded against the retreating ice margin. Shorelines observed in lidar data from Quebec (Ministère des Forêts, de la faune, et des parcs 2016) record a maximum water plane elevation of 230 m asl observed in the Laurentian Highlands 10 km north of the Ottawa River, possibly recording a northernmost limit for glacial Lake Candona. The lake is more commonly recorded by the deposition of finely laminated, rhythmically bedded muds with horizontal feeding traces (Al-Mufti et al. 2022) and is distinguished by the presence of freshwater ostracodes. One sampling site was selected because clay rhythmites directly overlie sands that are interpreted as the buried upflow portion of an esker that has been well studied by the GSC (*see* Figure 18.1A; Cummings et al. 2011; Pugin et al. 2009). Here, an intact succession of finely laminated, rhythmically bedded muds was observed, with a total of 61 couplets were counted in a rhythmite unit 0.8 m thick (*see* Figure 18.1B). If the couplets are varves representing annual deposition of summer silt and winter clays, this provides an estimate for the duration of glacial Lake Candona before marine inundation in this area, which is consistent with previous estimates (Occhietti 2007).

Once ice retreat exposed the St. Lawrence valley to the east, water levels fell by approximately 50 m and the Champlain Sea was established in the region (Lewis, Breckenridge and Teller 2021). Inundation by the Champlain Sea resulted in deposition of a thick succession of marine clays (*see* Figures 18.1B and 18.1C), before falling water levels resulted in reworking of sediments along shorelines to form abundant sand and gravel deposits along beaches between 100 and 185 m asl.

The last major events to shape the landscape in the City of Ottawa were floods routed down the Ottawa River from rapid drainage of upstream glacial lakes in northern and eastern Ontario. These floods caused major shifts in salinity in the Champlain Sea between 11.4 and 11.2 cal kyr BP (Cronin et al. 2008) and later carved large channels through marine clays and then fluviodeltaic sands were deposited as a broad sheet as the relative sea level in the region fell, terminating by 8.4 cal kyr BP (Brouard et al. 2021). Subaerial exposure of the large sand plains in the area, particularly south and east of the city, led to the formation of eolian dunes. Since deglaciation, river systems have been continuously downcutting through Quaternary sediments and the bedrock. Locally, this erosion has created steep slopes that create conditions that promote destabilization of the marine clays and lead to large retrogressive landslides (Brooks 2019).

Establishing a firm link between landform genesis in the City of Ottawa and elsewhere in Ontario remains challenging. Low precision and high uncertainty in available geochronological data, combined with a sparse landform record in adjacent shield terrain to the west, hinder inter-regional correlations. Ongoing mapping in the Lake Nipissing–Mattawa River lowlands (Marich, this volume) may help to provide further insights into the timing and relationships between the deglacial events in the Ottawa River valley and the Great Lakes basins.

FUTURE WORK

A geophysical survey is being planned for the City of Ottawa study area to better evaluate the sediment thickness and bedrock topography. A database of sediment lithology and sample results obtained from surficial sediment sections examined in this investigation is being assembled. Developing a more complete picture of water plane evolution and glacioisostatic uplift in the region is ongoing. Lidar data from Ontario and Quebec combined with age constraints provided by optically stimulated luminescence analyses will assist in these reconstructions, as well as improving correlation of events in the study area with other parts of Ontario.

ACKNOWLEDGMENTS

Nathan Mask provided capable and enthusiastic field assistance. Catherine Béland Otis provided helpful discussions on the characteristics of local bedrock strata. The National Capital Commission granted access to conduct research on their properties. George Gao is thanked for providing a technical review of this report. The author would like to thank the Algonquins of Pikwakanagan First Nation, Alderville First Nation, Curve Lake First Nation, Hiawatha First Nation, Métis Nation of Ontario Ottawa Region, Mississaugas of Scugog Island First Nation and the Mohawks of Akwesasne for allowing the Ontario Geological Survey to map their traditional land use area.

REFERENCES

Al-Mufti, O.N., Arnott, R.W.C., Hinton, M.J., Alpay, S. and Russell, H.A.J. 2022. Using computed tomography (CT) to reconstruct depositional processes and products in the subaqueous glaciogenic Champlain Sea basin, Ottawa, Canada; Geomorphology, v.403, paper 108165. doi.org/10.1016/j.geomorph.2022.108165

Barnett, P.J. 1988. History of the northwestern arm of the Champlain Sea; *in* The Late Quaternary development of the Champlain Sea Basin, Geological Association of Canada, Special Paper 35, p.25-36.

Brooks, G.R. 2019. Sensitive clay landslide inventory map and database for Ottawa, Ontario; Geological Survey of Canada, Open File 8600, 27p.

Brooks, G.R. and Adams, J. 2020. A review of evidence of glacially-induced faulting and seismic shaking in eastern Canada; Quaternary Science Reviews, v.228, paper 106070. doi.org/10.1016/j.quascirev.2019.106070

Brouard, E., Roy, M., Godbout, P.-M. and Veillette, J.J. 2021. A framework for the timing of the final meltwater outburst from glacial Lake Agassiz–Ojibway; Quaternary Science Reviews, v.274, paper 107260. doi.org/10.1016/j.quascirev.2021.107269

Brunton, F.R. 2013. Karst and hazards lands mitigation: Some guidelines for geological and geotechnical investigations in Ontario karst terrains; *in* Summary of Field Work and Other Activities, 2013, Ontario Geological Survey, Open File Report 6290, p.37-1 to 37-24.

——— 2019. Karst map of southern Ontario: An update; *in* Summary of Field Work and Other Activities, 2019, Ontario Geological Survey, Open File Report 6360, p.21-1 to 21-9.

Brunton, F.R. and Brintnell, C. 2020. Early Silurian Sequence stratigraphy and geological controls on karstic bedrock groundwater flow zones, Niagara Escarpment region and the subsurface of southwestern Ontario; Ontario Geological Survey, Groundwater Resources Study 13.

Cronin, T.M., Manley, P.L., Brachfeld, S., Manley, T.O., Willard, D.A., Guilbault, J.-P., Rayburn, J.A., Thunell, R. and Berke, M. 2008. Impacts of post-glacial lake drainage events and revised chronology of the Champlain Sea episode 13-9 ka; Palaeogeography, Palaeoclimatology, Palaeoecology, v.262, p.46-60.

Cummings, D.I., Gorrell, G., Guilbault, J.-P., Hunter, J.A., Logan, C., Ponomarenko, D., Pugin, A.J.-M., Pullan, S.E., Russell, H.A.J. and Sharpe, D.R. 2011. Sequence stratigraphy of a glaciated basin fill, with a focus on esker sedimentation; Geological Society of America Bulletin, v.123, p.1478-1496.

Dowling, T.P.F., Moller, P. and Spagnolo, M. 2016. Rapid subglacial streamlined bedform formation at a calving bay margin; Journal of Quaternary Science, v.31, p.879-892.

Kettles, I.M. and Shilts, W.W. 1989. Geochemistry of drift over the Precambrian Grenville Province, southeastern Ontario and southwestern Quebec; *in* Drift prospecting, Geological Survey of Canada, Paper 89-20, p.97-112.

Lewis, C.F.M., Breckenridge, A.J. and Teller, J.T. 2021. Reconstruction of isostatically-adjusted paleo-strandlines along the southern margin of the Laurentide Ice Sheet in the Great Lakes, Lake Agassiz, and Champlain Sea basins; Canadian Journal of Earth Sciences, v.59, p.826-846. doi.org/10.1139/cjes-2021-0005

Margold, M., Stokes, C.R. and Clark, C.D. 2018. Reconciling records of ice streaming and ice margin retreat to produce a palaeogeographic reconstruction of the deglaciation of the Laurentide Ice Sheet; Quaternary Science Reviews, v.189, p.1-30.

Medioli, B.E., Alpay, S., Crow, H.L., Cummings, D.I., Hinton, M.J., Knight, R.D., Logan, C., Pugin A.J.-M., Russell, H.A.J. and Sharpe, D.R. 2012. Integrated data sets from a buried valley borehole, Champlain Sea basin, Kinburn, Ontario; Geological Survey of Canada, Current Research 2012-3, 16p.

Ministère des Forêts, de la faune et des parcs 2016. Lidar elevation model; available from www.donneesquebec.ca/recherche/dataset/produits-derives-de-base-du-lidar (to see area of data, go to "Disponibilité du LiDAR - Modèles numériques (terrain, canopée, pente)") [accessed November 25, 2022].

Ministry of Natural Resources 2012. Ontario radar digital surface model; Ministry of Natural Resources, Land Information Ontario, Peterborough, Ontario.

Mulligan, R.P.M. 2019. Quaternary sediment mapping in the City of Ottawa, eastern Ontario; *in* Summary of Field Work and Other Activities, 2019, Ontario Geological Survey, Open File Report 6360, p.17-1 to 17-11.

Mulligan, R.P.M., Eyles, C.H. and Marich, A.S. 2019. Subglacial and ice-marginal landforms in south-central Ontario: Implications for ice-sheet reconfiguration during deglaciation; Boreas, v.47, p.635-657.

Occhietti, S. 2007. The Saint-Narcisse morainic complex and early Younger Dryas events on the southeastern margin of the Laurentide Ice Sheet; Géographie Physique et Quaternaire, v.61, p.89-117.

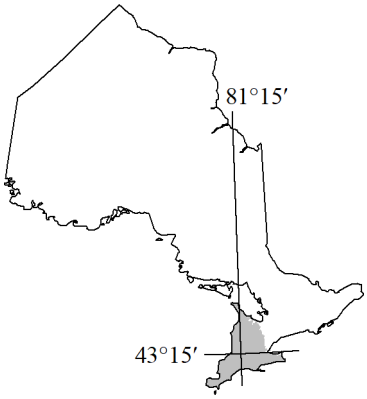
Pugin, A.J.-M., Pullan, S.E., Hunter, J.A. and Oldenborger, G.A. 2009. Hydrogeological prospecting using *P*- and *S*-wave landstreamer seismic reflection methods; Near Surface Geophysics, v.7, p.315-327.

Ross, M., Parent, M., Benjumea, B. and Hunter, J. 2006. The Late Quaternary stratigraphic record northwest of Montreal: Regional ice-sheet dynamics, ice stream activity, and early deglacial events; Canadian Journal of Earth Sciences, v.43, p.461-485.

Rust, B.R. 1988. Ice-proximal deposits of the Champlain Sea at South Gloucester, near Ottawa, Canada; *in* The Late Quaternary development of the Champlain Sea Basin, Geological Association of Canada, Special Paper 35, p.37-46.

Sharpe, D.R. 1988. Glaciomarine fan deposition in the Champlain Sea; *in* The Late Quaternary development of the Champlain Sea Basin, Geological Association of Canada, Special Paper 35, p.63-82.

19. Project SO-20-001. Subsurface Stratigraphy of Early Silurian Medina Group Mixed Siliciclastic–Carbonate Strata, Southwestern Ontario: Final Update



R.H. Paterson[1], F.R. Brunton[1,2], J. Jin[1], A.R. Phillips[1] and K.H. Yeung[2]

[1]Department of Earth Sciences, The University of Western Ontario, London, Ontario N6G 2V4
[2]Earth Resources and Geoscience Mapping Section, Ontario Geological Survey, Sudbury, Ontario P3E 6B5

INTRODUCTION

This report summarizes observations from subsurface cores of key formations of the early Silurian Medina Group under eastern and central Lake Erie and onshore in southwestern Ontario (*see* Paterson et al. 2020, 2021). This study forms part of a MSc thesis by the senior author at The University of Western Ontario and is supported by several agencies, including the Ontario Geological Survey, the Oil, Gas and Salt Resources Library in London, Ontario, and the Mitacs Accelerate Program at the University of Western Ontario (for details, *see* "Acknowledgments").

The Medina Group comprises siliciclastic (sandstone and shale) and minor carbonate sedimentary rocks that crop out and subcrop along the Niagara Escarpment and occur in subsurface across parts of southwestern Ontario. Although stratigraphic studies of Silurian strata began in the Niagara region more than 150 years ago (Logan et al. 1863; Williams 1919; Bolton 1953, 1957, 1965; Sanford 1969; Brett et al. 1995), there is still much detailed work to be done regarding characterization of formational top picks and lithofacies descriptions of key rock units (*see* discussion in Paterson et al. 2020, 2021; Figure 19.1). The Medina Group contains several formations, including, in descending order, the Kodak, Cambria, Thorold, Grimsby, Devils Hole, Ball's Falls, Power Glen, Cabot Head and Whirlpool formations (for the evolution of stratigraphic nomenclature, refer to Telford 1978; Johnson et al. 1992; Brett et al. 1995; Brunton et al. 2017; Brett, Brunton and Calkin 2018; Brunton and Brintnell 2020; *see* Figure 19.1). The Grimsby, Thorold and Whirlpool formations are important natural gas reservoirs that occur both onshore and offshore in southwestern Ontario (most of the larger active natural gas pools occur under Lake Erie; Figure 19.2).

Some of the formations in the Medina Group do not have adequate type section descriptions and, therefore, confusion exists in relating the vertical changes in lithofacies to the geophysical log signatures in the boreholes. This study aims to improve our understanding of the regional lithostratigraphic architecture of these units in the subsurface of southwestern Ontario by combining detailed core logging and drill-cuttings descriptions, integrating geophysical logs, and field observations of select outcrops.

GEOLOGICAL SETTING

The bedrock geology of southern Ontario comprises up to 1400 m of Paleozoic sedimentary strata that range from upper Cambrian to Carboniferous (Mississippian) (Johnson et al. 1992; Armstrong and

Summary of Field Work and Other Activities, 2022,
Ontario Geological Survey, Open File Report 6390, p.19-1 to 19-9.

© King's Printer for Ontario, 2022

Carter 2010). Present-day southern Ontario was positioned in subtropical latitudes during the depositional and erosional history of the Clinton and Medina successions (Johnson et al. 1992; Cocks and Torsvik 2011; Jin et al. 2013; Jin, Zhan and Wu 2018). Previous work on the lower Silurian siliciclastic succession in southwestern Ontario was summarized in Paterson et al. (2021) and is not repeated here. Most importantly though, a total of 1635 wells have been drilled in Lake Erie in the 53 years since Beards' (1967) work to merge outcrop stratigraphic nomenclature with subsurface nomenclature, pointing to the need for restudy.

The depositional environment during the early Silurian consisted of shallow epeiric seas and deltaic and/or estuarine environments, reflecting diverse environments from nonmarine sandstones to marine shales and sandstones and shallow marine carbonates (Brett et al. 1995; Brunton and Brintnell 2020). This succession accumulated on the far-field side of the Appalachian foreland basin within a regionally extensive ramp on the Laurentia craton that was subjected to sea-level drawdown during the Late Ordovician and early Silurian glacial and interglacial phases, and episodic forebulge migration tectophases and associated sea-level fluctuations (Brett, Goodman and LoDuca 1990; Cheel 1991; Brett et al. 1995; Brunton et al. 2012; Brunton and Brintnell 2020). Geographically, the northern flank of the Appalachian foreland basin is present in southern Ontario, with many of the strata of the Clinton and Medina groups showing thinning and pinch outs (representing subregional disconformities) from east-central Lake Erie into southwestern Ontario (Martini 1971, 1974a, 1974b; Duke and Brusse 1987; Brett, Goodman and LoDuca 1990; Cheel 1991; Brett et al. 1995; Brunton et al. 2012, 2017; Brunton and Brintnell 2020).

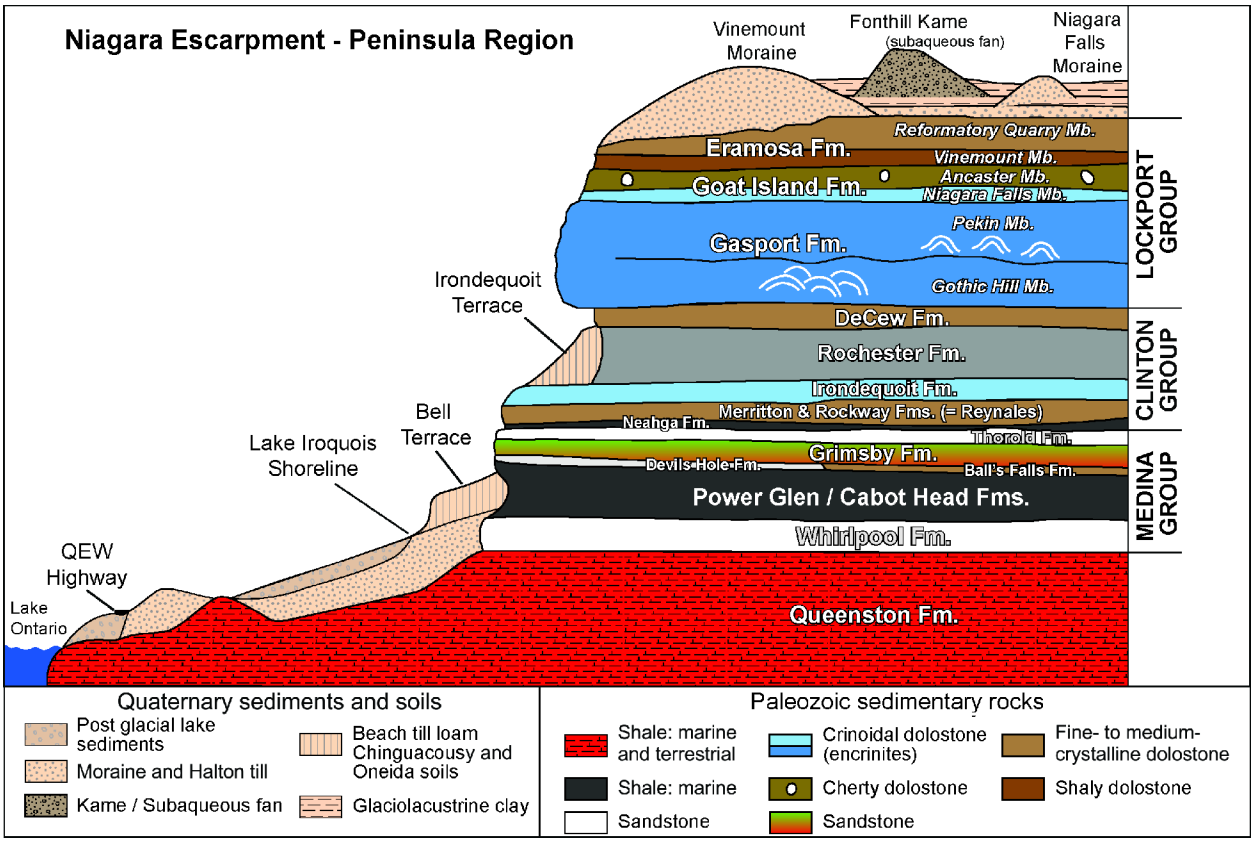


Figure 19.1. Upper Ordovician and early Silurian Paleozoic stratigraphy and simplified Quaternary geology of the Niagara Peninsula region, southwestern Ontario (*modified from* Haynes 2000; Brunton and Brintnell 2020). The Guelph Formation (not shown) is generally not found at or near the edge of the Niagara Escarpment or cuesta margin in the Niagara region.

Medina Group Cores

The lithological descriptions of cores, including the interpretation and integration of geophysical well logs have aided in the delineation of Medina Group formational-rank contacts. Five cores have been selected as reference cores (*see* Figure 19.2) as they have the most complete section of the rock units. From east to west, these cores are

- core 173, Consumers' 32271, Wainfleet 2-2-III, Licence # T003723
- core 229, Anschutz, Haldimand Lake Erie 22-S-4, Licence # T003853
- core 371, Anschutz, Norfolk Lake Erie 92-N-3, Licence # T003792
- core 1001, Consumers'- Amoco 13102, Norfolk Lake Erie 96-D-1, Licence # T002803
- core 999, Consumers'- Pan Am 13057, Elgin Lake Erie 56-E-3, Licence # T002759

Research has focussed on detailed logging of lithology, sedimentary structures, fauna, and diagenetic alterations of the cores. A total of 47 representative cores have also been logged, as summarized by Paterson et al. (2021, p.18-5).

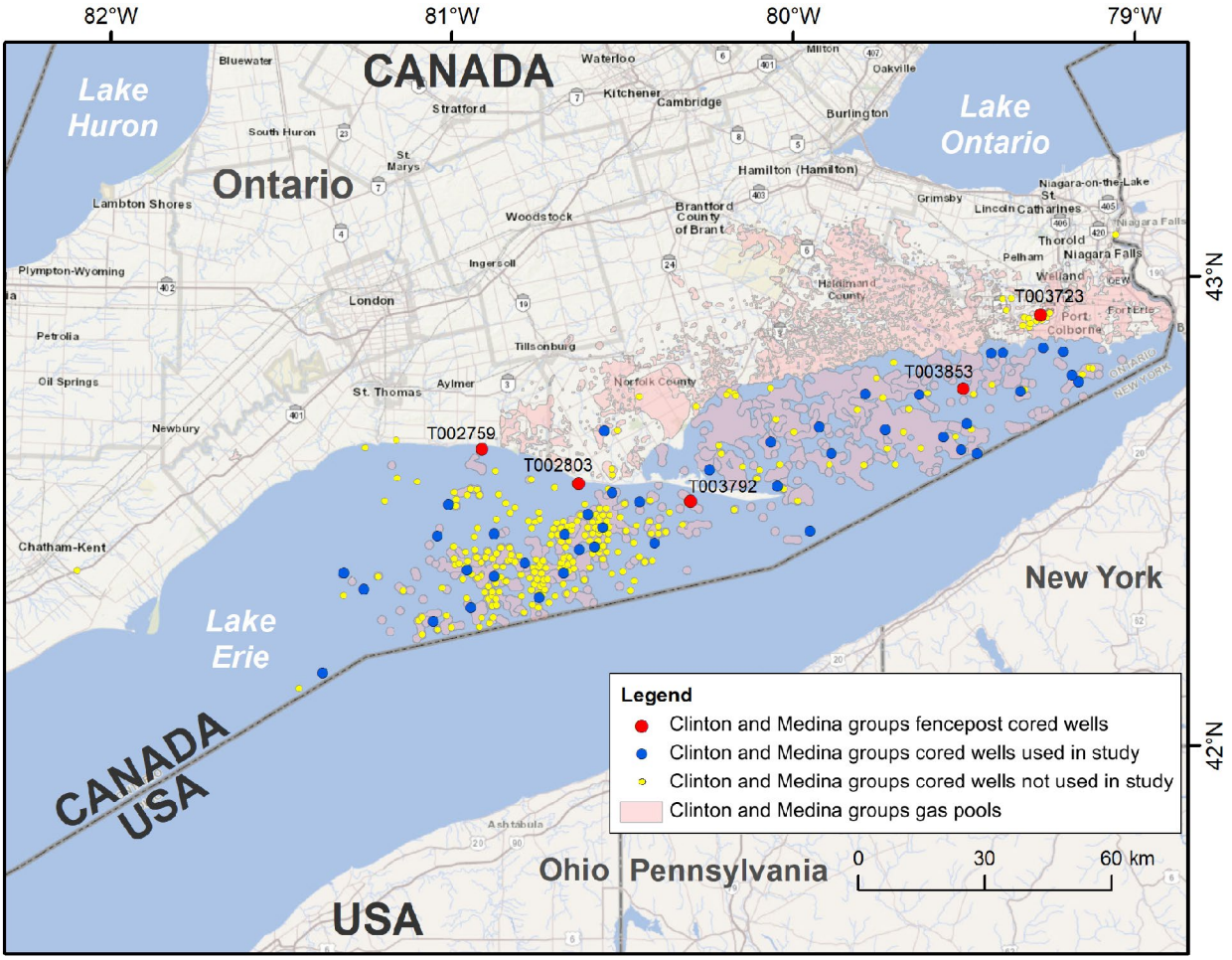


Figure 19.2. Distribution map of a) fencepost wells (red dots) described in the text used in regional correlation; b) priority and secondary wells (blue dots) in the Clinton and Medina groups with porosity and/or permeability data used in this study (wells listed in Paterson et al. 2021, p.18-5); c) all exploration wells (yellow dots) in the Clinton and Medina groups, as identified in the Ontario Petroleum Data System; and d) Clinton and Medina group gas pools (pale pink fill) (data *from* Oil, Gas and Salt Resources Library, London, Ontario). More than 10 000 oil and gas exploration wells (not all indicated) penetrate parts of lower Silurian strata in southwestern Ontario.

QUEENSTON FORMATION

The Queenston–Whirlpool formations contact interval is best developed in core 173, which is regarded as the reference core section for this contact in this study area. Here, the top is picked at 221.13 m in core 173, licence # T003723. Starting at this depth, the Queenston Formation is marked by a reddish brown–maroon to green, blocky pieces of mudstone, and referred to as "Unit 1" in this study. Typically, the top of the Queenston Formation changes from a reddish-maroon shale to an extremely fissile shale, often green at the contact, that is disconformably overlain by the Whirlpool Formation. The top unit of the formation can be traced regionally from cores 173 to 1001 as a reddish brown–maroon to green, extremely fissile, colored shale. To the east, Unit 1 changes from shale to a thick, light grey to green dolomudstone facies (e.g., cores 999 and 1001).

WHIRLPOOL FORMATION

The Whirlpool–Queenston formation contact interval is best developed in core 229, which is regarded as the reference core section for this contact in this study at a depth of 326.40 m. The Whirlpool Formation is characterized by a white or grey to tan, fine- to medium-sand–grade quartzose sandstone with dark and/or light grey shale rip up clasts and laminae. As mentioned by previous authors (e.g., Martini and Salas 1983), the Whirlpool Formation can be subdivided into an Upper and Lower unit, representing a shallow water nearshore marine environment and a braided fluvial environment, respectively. In core 229, fluctuations in gamma-ray log responses reflect these changes in lithofacies, showcasing changes from white, fine- to medium-sand–grade quartzose sandstone transitioning into a heavily shale parted facies. The Whirlpool Formation overlies the Queenston Formation in the study area, but there are locations where dolostones of the Manitoulin Formation disconformably overlie the Queenston Formation. The Whirlpool Formation can be traced laterally and can be found beyond the study area in southwestern Ontario. A thin remnant persists and pinches out into central Lake Erie.

MANITOULIN FORMATION

Previous literature has described the contact between the underlying Whirlpool Formation as gradational when both units are present; therefore, supporting evidence from the geophysical logs is needed to pick the contact. Additional study indicates that the Manitoulin Formation lower contact interval is best developed in core 371, rather than core 1001 as suggested in Paterson et al. (2021). Core 371 is regarded as the reference core section for this contact in this study area. The Manitoulin Formation is predominantly a dolostone, with minor grey or green shale interbeds toward the top of the unit, that grade into the overlying Cabot Head Formation shales. In core 371, there is a sharp, erosive contact at depths 466.60 m. In core 1001, the Manitoulin Formation contact with the Whirlpool Formation is sharp, displaying a colour change from reddish-brown to light grey and lithofacies changes from interbedded shale to mottled dolostones at a depth of 463.60 m.

CABOT HEAD FORMATION

The Cabot Head Formation lower contact interval is best developed in cores 1001 and 999. The formation can be traced laterally and regionally from Lake Erie to the Bruce Peninsula and Manitoulin Island and is expressed differently in all these locations. In the western and central part of the study area, the Cabot Head Formation consists of dark grey dolomitic sandstone and silt and/or shale interbeds, and dark grey to brown–maroon shales with fine-silt–grade quartz lenses. Boxes 118–125 of core 1001 show predominantly medium grey shale with thin silty dolomitic sandstone laminations and interbeds. Boxes 111–117 of core 999 show predominantly medium grey shale with thin silty dolomitic fossiliferous sandstone laminations and interbeds. The contact is difficult to delineate in geophysical logs, so both core and geophysical logs are needed to distinguish the contact and to extrapolate to wells with poor geological control.

POWER GLEN FORMATION

The Power Glen Formation lower contact interval is present in the eastern part of the study area, and is best developed in core 173, at a depth of 207.50 m. The unit is a dark grey fissile shale with silty sand lenses, grading upward into the overlying Devils Hole Formation and Artpark phosphate interval. There is a very sharp contact in the geophysical log at depth 208.79 m. Both core and geophysical logs are needed to delineate the contact.

DEVILS HOLE FORMATION

The Devils Hole Formation lower contact interval is best developed in cores 999 and 1001 at depths of 430.380 m and 443.79 m, respectfully. Both core and geophysical logs are needed to distinguish the contact and to extrapolate to wells with less geological control. The Devils Hole Formation thickens eastward and southward as sediment supply became more available. This formation can be described as grey to red to maroon, fossiliferous and heavily horizontally burrowed, with phosphatized nodules, grading into red-maroon fine sand quartzose sandstones and silt and/or shale interbeds along with massive sandstones with blotchy staining and liesegang banding. All of these features can be seen in core 1001, which is regarded as the reference well for this section.

PHOSPHATE MARKER BED

The presence of the Artpark phosphate interval can be seen in the eastern part of the study area in cores 173 and 229 at a depth of 207.26 m and 305.10 m, respectively. This interval, within the Devils Hole Formation, consists of a distinctive phosphate bed up to 0.3 m thick in these 2 cores. This bed provides the contact between the Devils Hole and Grimsby formations in cores 173 and 229 only. In the western and central part of the study area, the Artpark phosphate interval diminishes into a small phosphatic bed and/or nodules across the study area, dissipating westward.

GRIMSBY FORMATION

The Grimsby Formation upper contact is best developed in core 173, which is regarded as the reference core section for this formation. The formation consists of red, grey or white and green, fine- to medium-sand–grade sandstones that are interbedded with silt and shale partings. The Grimsby Formation, in core 173, displays a change from reddish-brown to gray-green fissile shale to white, red-stained fine–grade sandstone with extremely thin shale interbeds. In the other 4 fencepost cores, the Grimsby Formation upper contact consists of massive reddish brown, fine- to medium-sand–grade sandstone with very little shale present, leaving only portions of the sandstone white in irregular blotches. The amalgamation of red to maroon fossiliferous packstone beds in the Grimsby Formation rather than the Cabot Head Formation is interpreted to reflect shifting depositional environments. These packstone beds can be traced from the western to the central part of the study area, and can be seen in cores 999, 1001 and 371. This upper contact is difficult to pick regionally because of the extreme variability of the lithofacies, with colour change being one variable.

THOROLD FORMATION

The Thorold Formation lower contact interval is best developed in core 173. This formation is characterized by grey to green to white, fine- to medium-sand–grade massive quartz sandstone beds with silty and/or shale partings and laminae. In other areas, the Thorold and Grimsby formations can be confused with one another because of their similar colours and siliciclastic characteristics. The boundary between the Thorold Formation and overlying sedimentary rock units of the Clinton Group, which can

vary from the Neagha, Cambria, Kodak and Merritton formations, is sharp and complicated, and is beyond the scope of this study. In core 173, the transition from shale to white massive fine-sand–grade quartz sandstones is observed at a depth of 187.76 m. In core 229, the contact between the Merritton Formation dolostones and the Neagha Formation shales and the underlying Thorold Formation is at 289.56 m. In core 229, the uppermost boundary between the Thorold Formation and overlying Merritton Formation, at a depth of 288.81 m, is characterized by the presence of brachiopod shells and black chert nodules, along with a colour change from gray to green to white shale and sandstone unit to a white to tan to grey dolomitic unit, and likely represents a disconformity.

RESULTS

This study involved the logging and photography of 23 priority cored wells and 24 secondary cored wells from the more than 260 wells that penetrate the Clinton and/or Medina Group succession in the study area (*see* Figure 19.2). Emphasis was placed on selecting cored wells spaced across the study area to assess variations in lithofacies and establish a predictive stratigraphic architecture.

This study recognizes 3 major sedimentary packages in the Medina Group in the subsurface of southwestern Ontario. Based on examination of the 47 cored or partially cored wells, in combination with geophysical borehole logs, the stratigraphic boundaries for these formations have been refined, as described in "Medina Group Cores" and in the following summary. Complete results can be found in Paterson (2022).

The Manitoulin Formation carbonate and Whirlpool Formation siliciclastic facies comprise a thin package, but with laterally consistent thickness, that overlie strata of a peneplaned uppermost Ordovician Queenston Formation. The contact between Queenston and Whirlpool formations is distinct in geophysical logs. In contrast, the Whirlpool to Manitoulin formation transition is difficult to delineate in geophysical logs, but can sometimes be seen as a very slight inflection in the logs. Generally, core and cuttings are needed to confirm this transition in some areas. This carbonate to siliciclastic rock transition within the Whirlpool and Manitoulin formations also has a distinct facies transition zone, from mixed carbonate-siliciclastic rocks in the west to predominantly siliciclastic rocks in the eastern part of the study area. The contact between the carbonate–siliciclastic facies can be described as white to grey to tan fine–grade sandstone interbedded with fine–grade sand to silt changing laterally to grey to tan fine–grade dolostone, with abundant fossiliferous material interbedded within the dolomudstone and dolomitic sandstone to the west.

Overlying disconformably these strata are the Cabot Head Formation shales and the Power Glen Formation dark grey and/or green shales and sandstones. The depositional package in these 2 formations is complex, having a greater range of lithological variation that is dominated by shale with minor siltstone and sandstone interbeds or lenses. The contacts between these different rock units are difficult to delineate without the use of core. In the western part of the study area, the Cabot Head Formation lower contact is at the first occurrence of a white to tan fine–grade dolomitic sandstone bed, fining upward to a grey fine–grade dolomitic siltstone and interbedded with said dolomitic sandstone. The Cabot Head Formation grades laterally into the Power Glen Formation in the central-eastern part of the study area, where the contact with the underlying Whirlpool Formation is sharp, changing from a white to tan fine–grade sandstone to dark grey to black fissile shale with thick white fine–grade sandstone beds.

The overlying Devils Hole Formation has a slight colour and compositional change compared to the Cabot Head Formation shale and is more abundant in the eastern part of the study area. The shale and dolomitic beds of the Devils Hole Formation are dark grey to green to fine–grade silt and shale beds interbedded with bedded fine–grade sandstone beds. The presence of phosphate nodules aids in the delineation of the contact between the Devils Hole Formation and the overlying Grimsby Formation.

The Grimsby Formation marks the beginning of a transgressive depositional system in the south and eastern part of the study area, and is characterized by interbedded red and green sandstones, siltstones and shales, with multiple thin beds of bryozoan biostromes in the western part of the study area. The lower and middle part of the Grimsby Formation suggests normal marine depositional environments. The presence of fossiliferous interbeds in the Grimsby versus the Cabot Head formations is noteworthy, and a possible subject for future work. The upper part of the Grimsby Formation is massive, fine-sand–grade quartz arenite with swaley cross-stratification and the presence of *Arthrophycus* burrows. The transition from the Cabot Head Formation succession to the Grimsby Formation facies is difficult to delineate on geophysical logs; core and drill cuttings are required to distinguish the underlying units. The presence of the Artpark Phosphate marker bed in the eastern part of the study area provides a subregional marker bed marking the base of the Grimsby Formation.

The overlying Thorold Formation represents the topmost sandstone of the Medina Group. It commonly comprises light grey quartz arenites, which may change to a burrowed and chaotically bioturbated lithofacies. This formation represents the last stage of a shallowing upward succession as part of a prograding siliciclastic system. The contact with the underlying Grimsby Formation is difficult to discern because of the distinct colour and similar features between the Grimsby and Thorold formations. The contact between them can be inferred using both geophysical logs and cores and/or drill cuttings. The upper contact of the Thorold Formation with the Clinton Group is described as white to tan to green, fine–grade sandstone with interbedded dark grey to green shale and abundant burrows.

Two phosphate marker beds have been identified that are useful for subregional stratigraphic correlations. The Artpark phosphate marker bed is used to delineate the contact between the Devils Hole and the Grimsby formations. The Densmore Creek marker bed, not described herein, occurs in strata that sit atop the Thorold Formation, reflecting a disconformity.

ACKNOWLEDGMENTS

The COVID-19 pandemic restrictions limited access to cores and outcrops during this study, thereby extending the time required to undertake the necessary work. Consequently, the study was modified to focus on Medina Group strata. This study forms part of a MSc thesis by the senior author (RHP) at The University of Western Ontario and is supported by several agencies: the Ontario Geological Survey (OGS); a Natural Sciences and Engineering Research Council (NSERC) grant to Dr. Jisuo Jin at The University of Western Ontario, London, Ontario; the Ontario Petroleum Institute (OPI); and the Oil, Gas and Salt Resources Library in London, Ontario, through the Mitacs Accelerate Program at The University of Western Ontario. This article fulfills part of the requirements for the Mitacs Accelerate Program. The authors thank Jordan Clark (Manager of the Oil, Gas and Salt Resources Library) for co-ordinating access to library, digital records, core handling and photography.

REFERENCES

Armstrong, D.K. and Carter, T.R. 2010. The subsurface Paleozoic stratigraphy of southern Ontario; Ontario Geological Survey, Special Volume 7, 301p.

Beards, R.J. 1967. Guide to the subsurface Palaeozoic stratigraphy of southern Ontario; Ontario Department of Energy Resources Management, Paper 67-2, 19p.

Bolton, T.E. 1953. Silurian formations of the Niagara Escarpment in Ontario; Geological Survey of Canada, Paper 53-23, 19p.

——— 1957. Silurian stratigraphy and paleontology of the Niagara Escarpment in Ontario; Geological Survey of Canada, Memoir 289, 145p.

——— 1965. Pre-Guelph, Silurian formations of the Niagara Peninsula, Ontario; *in* Geology of Central Ontario, Michigan Basin Geological Society, Field Trip Guidebook, p.55-80.

Brett, C.E., Brunton, F.R. and Calkin, P.E. 2018. Sequence stratigraphy and paleontology of the classic Upper Ordovician–Silurian succession in Niagara County, New York – with supplement on Quaternary geology of western New York; Association of Earth Science Editors, 52nd Annual Meeting, September 26–29, 2018, Niagara Falls, New York, Field Trip Guidebook, 191p.

Brett, C.E., Goodman, W.M. and LoDuca, S.T. 1990. Sequences, cycles, and basin dynamics in the Silurian of the Appalachian Foreland Basin; Sedimentary Geology, v.69, p.191-244.

Brett, C.E., Tepper, D.H., Goodman, W., LoDuca, S.T. and Eckert, B.-Y. 1995. Revised stratigraphy and correlations of the Niagaran Provincial Series (Medina, Clinton and Lockport groups) in the type area of western New York; United States Geological Survey, Bulletin 2086, 66p.

Brunton, F.R. and Brintnell, C. 2020. Early Silurian sequence stratigraphy and geological controls on karstic bedrock groundwater flow zones, Niagara Escarpment region and the subsurface of southwestern Ontario; Ontario Geological Survey, Groundwater Resources Study 13.

Brunton, F.R., Brintnell, C., Jin, J. and Bancroft, A.M. 2012. Stratigraphic architecture of the Lockport Group in Ontario and Michigan – A new interpretation of Early Silurian "basin geometries" and "Guelph pinnacle reefs"; *in* Proceedings, Ontario Petroleum Institute, 51st Annual Conference, Niagara Falls, Ontario, v.51, Technical Paper 8, p.1-37.

Brunton, F.R., Carter, T., Logan, C., Clark, J., Yeung, K., Fortner, L., Freckelton, C., Sutherland, L. and Russell, H.A.J. 2017. Lithostratigraphic compilation of Phanerozoic bedrock units and 3D geological model of southern Ontario; abstract *in* Regional-scale groundwater geoscience in southern Ontario: An Ontario Geological Survey, Geological Survey of Canada, and Conservation Ontario Geoscientists open house, Guelph, Ontario, March 1–2, 2017, Geological Survey of Canada, Open File 8212, p.3. doi:10.4095/299759

Cheel, R.J. ed. 1991. Sedimentology and depositional environments of Silurian strata of the Niagara Escarpment, Ontario and New York; Geological Association of Canada–Mineralogical Association of Canada–Society of Economic Geologists, Joint Annual Meeting, Toronto 1991, Field Trip B4 Guidebook, 99p.

Cocks, L.R.M. and Torsvik, T.H. 2011. The Palaeozoic geography of Laurentia and western Laurussia: A stable craton with mobile margins; Earth-Science Reviews, v.106, p.1-51.

Duke, W.L. and Brusse, W.C. 1987. Cyclicity and channels in the upper members of the Medina Formation in the Niagara Gorge; *in* Sedimentology, stratigraphy and ichnology of the Lower Silurian Medina Formation in New York and Ontario, Eastern Section of the Society of Economic Paleontologists and Mineralogists, Guidebook for the 1987 Annual Field Trip, p.46-65.

Haynes, S.J. 2000. Geology and Wine 2. A geological foundation for terroirs and potential sub-appellations of Niagara Peninsula wines, Ontario, Canada; Geoscience Canada, v.27, p.67-87.

Jin, J., Harper, D.A.T., Cocks, R.M., McCausland, P.J.A., Rasmussen, C.M.O. and Sheehan, P.M. 2013. Precisely locating the Ordovician equator in Laurentia; Geology, v.41, p.107-110.

Jin, J., Zhan, R. and Wu, R. 2018. Equatorial cold-water tongue in the Late Ordovician; Geology, v.46, p.759-762.

Johnson, M.D., Armstrong, D.K., Sanford, B.V., Telford, P.G. and Rutka, M.A. 1992. Paleozoic and Mesozoic geology of Ontario; Chapter 20 *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 2, p.907-1008.

Logan, W.E., Murray, A., Hunt, T.S. and Billings, E. 1863. Geology of Canada. Report of Progress from its Commencement to 1863, Geological Survey of Canada, 983p.

Martini, I.P. 1971. Regional analysis of sedimentology of Medina Formation (Silurian), Ontario and New York; American Association of Petroleum Geologists Bulletin, v.55, p.1249-1261.

——— 1974a. Deltaic and shallow marine Lower Silurian sediments of the Niagara Escarpment between Hamilton, Ont. and Rochester, N.Y. – A field guide; Maritime Sediments, v.10, no.2, p.52-66.

——— 1974b. Environments of deposition of the Medina (Grimsby) Formation, and exploration for hydrocarbons; *in* Proceedings, Ontario Petroleum Institute, 13th Annual Conference, London, Ontario, v.13, Technical Paper 7, 18p.

Martini, I.P. and Salas, C. 1983. Depositional characteristics of the Whirlpool Sandstone, Lower Silurian, Ontario; Ontario Geological Survey, Open File Report 5363, 124p.

Paterson, R.H. 2022. Subsurface correlation of the Silurian Medina Group, southwestern Ontario; unpublished MSc thesis, The University of Western Ontario, 150p.

Paterson, R.H., Brunton, F.R., Jin, J., Phillips, A.R., Yeung, K.H. 2020. Subsurface correlation of the Silurian Clinton and Medina groups, southwestern Ontario; *in* Summary of Field Work and Other Activities, 2020, Ontario Geological Survey, Open File Report 6370, p.15-1 to 15-9.

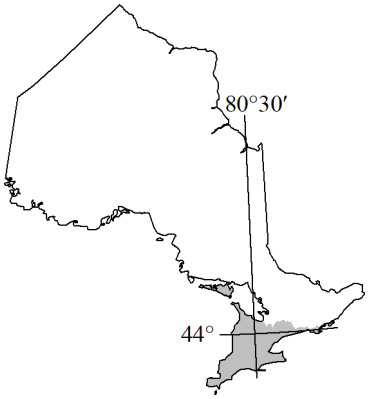
——— 2021. Subsurface correlation of the Silurian Clinton and Medina groups, southwestern Ontario; *in* Summary of Field Work and Other Activities, 2021, Ontario Geological Survey, Open File Report 6380, p.18-1 to 18-11.

Sanford, B.V. 1969. Silurian of southwestern Ontario; *in* Proceedings, Ontario Petroleum Institute, 8th Annual Conference, Toronto, Ontario, v.8, Technical Paper 5, 44p.

Telford, P.G. 1978. Silurian stratigraphy of the Niagara Escarpment, Niagara Falls to the Bruce Peninsula; *in* Toronto ’78 Field Trips Guidebook, Geological Society of America–Geological Association of Canada–Mineralogical Association of Canada, Joint Annual Meeting, p.28-42.

Williams, M.Y. 1919. The Silurian geology and faunas of Ontario Peninsula, and Manitoulin and adjacent islands; Geological Survey of Canada, Memoir 111, 195p.

20. Project SO-21-002. Stratigraphy and Sedimentology of Upper Ordovician Strata, with Emphasis on the Collingwood and Rouge River Members, Southern Ontario and Manitoulin Island



D. Atasiei[1], C.J. Tsujita[1], F.R. Brunton[1,2], J. Jin[1] and K.H. Yeung[2]

[1]Department of Earth Sciences, University of Western Ontario, London, Ontario N6G 2V4
[2]Earth Resources and Geoscience Mapping Section, Ontario Geological Survey, Sudbury, Ontario P3E 6B5

INTRODUCTION

Although the Ordovician stratigraphy of southern Ontario has been studied for more than a century, several inconsistencies remain between surface and subsurface stratigraphic nomenclature. Rock units with the same stratigraphic name have different lithologic and/or paleontological definitions and subdivisions depending on their geographic location. The Upper Ordovician carbonate-dominated succession of Ontario occurs in a large area along the St. Lawrence Platform, extending from the Ottawa region to the Niagara Escarpment and to Windsor. This carbonate depositional system was punctuated by a suite of organic-rich shales and mixed shale-carbonate units between the lower Katian (Trentonian) normal marine carbonates of the underlying Verulam–Cobourg formations and the overlying upper Katian Blue Mountain and Georgian Bay formations.

One of the main goals of this study is to compare the stratigraphic-rank criteria for the Upper Ordovician succession in southern Ontario, including, in ascending order: the Collingwood member of the Cobourg Formation of the Trenton Group (should the member be a formational rank unit and how does it correlate with the Utica Formation regionally); and the Rouge River member of the overlying Blue Mountain Formation. At present, no systematic formation-rank picks or stratigraphic nomenclature have been agreed upon for these Upper Ordovician strata in southern Ontario.

This work will build upon the collaborative studies (2015 to 2022) between the Ontario Geological Survey (OGS), the Geological Survey of Canada (GSC), the staff of the Oil, Gas and Salt Resources Library (OGSRL), and faculty and students of the Department of Earth Sciences of the University of Western Ontario (UWO), to create the first three-dimensional (3-D) Paleozoic bedrock Leapfrog® Works model for south-central and southwestern Ontario (Brunton et al. 2017; Carter et al. 2019, 2020, 2021; Brunton and Brintnell 2020). The broader objective of this study is to provide an interpretation of the environmental factors that led to the disappearance of the widespread carbonate factory and the subsequent accumulation of organic-rich Collingwood member and Rouge River member carbonate and shale rock units, respectively. In recent years, there have been numerous studies concerning the Late Ordovician environmental crisis and ocean anoxia based on widespread black shales.

Summary of Field Work and Other Activities, 2022,
Ontario Geological Survey, Open File Report 6390, p.20-1 to 20-6.

© King's Printer for Ontario, 2022

PREVIOUS WORK

The historical development of stratigraphic nomenclature for the Upper Ordovician in southern Ontario is complex (Figure 20.1). Raymond (1914) introduced the term "Collingwood" and, over the past century, it has undergone many changes in stratigraphic position and formational rank and has also been

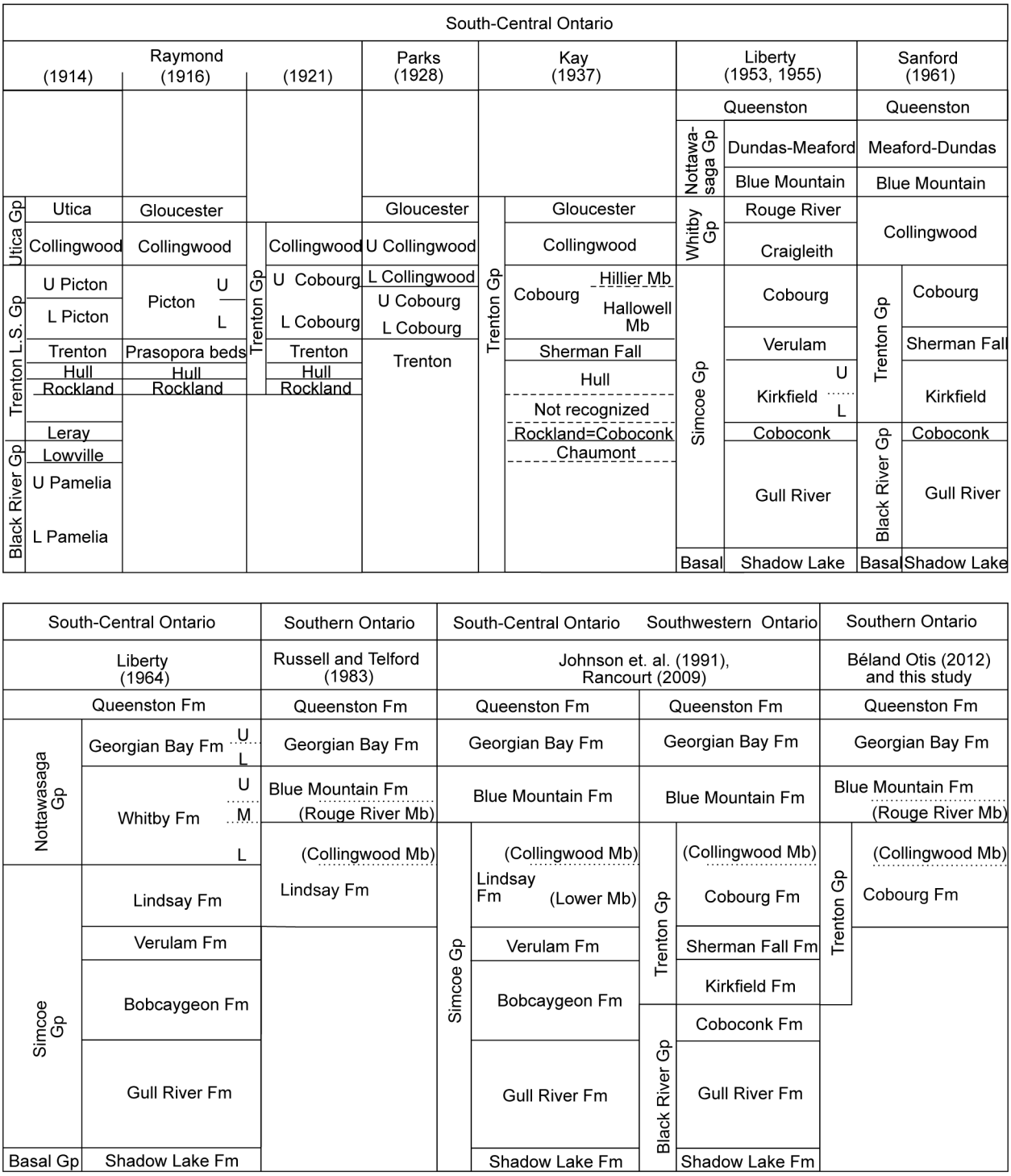


Figure 20.1. Selected stratigraphic nomenclature chart for part of the Upper Ordovician Paleozoic geology in southern Ontario Abbreviations: Fm, Formation; Gp, Group; L, lower; Mb, member, U, upper.

Table 20.1. Wells selected for subsurface stratigraphic study of the Cobourg Formation, focussing on the Collingwood and the Rouge River members of the Blue Mountain Formation. Cores with photos have been logged and the formation picks are summarized in the records of the Oil, Gas and Salt Resources Library in London, Ontario.

Licence Number	Name	Core Number	Photographed (Yes or No)	Latitude (degrees North)	Longitude (degrees West)
T012159	Dundee East, Lake Erie 45 - E4C	1130	No	42.73641667	−80.07358333
T006120	OGS 83-1 Halton, Nassagaweya 9-VII	1104	Yes	43.53479139	−79.95857611
T006056	OGS 82-4 Wiarton, Albemarle 4-24-1W	862	Yes	44.79185583	−81.23234972
T002252	Geological Survey of Canada No 2, Russell 24-II	151	Yes	45.32047222	−75.39594444
T006078	OGS 82-3, Yarmouth Township, 3-9-1	861	Yes	42.67076833	−81.16139472
T006045	OGS 82-2 Chatham, Harwich 1-25-IECR	860	Yes	42.38782250	−82.07989500
H000015	OGS Deep Hole No. 1 Corbetton, Melancthon 251-II	1098	Yes	44.14021583	−80.35862222
N000262	OGS CLGD No. 1, Collingwood 27-VII	CLGD 1	No	44.53397972	−80.41429167
N000257	OGS CLGD No. 2, Collingwood 24-VIII	CLGD 2	No	44.51392000	−80.42696250
N000261	OGS CLGD No. 3, Collingwood 26-VII	CLGD 3	No	44.53286306	−80.39755917
N000258	OGS CLGD No. 4B, Collingwood 25-IV	CLGD 4B	No	44.53420194	−80.35379000
N000255	OGS CLGD No. 7A, Collingwood 10-I	CLGD 7A	No	44.46744194	−80.27927000
N000264	OGS CLGD No. 16, Collingwood 40-XII	CLGD 16	No	44.58801639	−80.51334639

assigned to different stratigraphic groups (e.g., Simcoe Group versus Trenton Group). Likewise, the term "Rouge River" has been referred to under different names (e.g., originally "Gloucester" by Raymond (1914) and "Whitby" by Liberty (1964) and assigned different stratigraphic rank (e.g., formation versus member).

Although the authors agree with the latest stratigraphic assignments of lithofacies by the OGS (*see* Béland Otis 2012), some discrepancies remain regarding formational-rank picks for some of the wells examined this summer and additional study is underway.

OBJECTIVES

The main objectives of this study are to characterize and redefine formational rank picks of the Cobourg Formation through the Blue Mountain Formation succession, building upon previous work, and provide quality assurance and quality control (QA–QC) criteria for key Upper Ordovician regional cored wells.

A total of 13 cores were examined in the summer of 2022 (*see* Figure 20.1; Table 20.1) at various sites in southern Ontario. Key cores were chosen based upon completeness of available core coverage and geophysical data through the interval of interest and regional coverage (Figure 20.2). Drill core observations of Collingwood member strata made during the summer of 2022 were supplemented by field observations on outcrops at Delphi Point (not shown on map) on the southern shore of Georgian Bay. An additional 7 cores are to be examined in the fall of 2022 to expand the regional coverage.

RESEARCH METHODS

Quality assurance of the formation top picks combine lithofacies descriptions of rock core and cuttings relative to geophysical well logs (gamma-ray–neutron–density) combined with key outcrop sections. Field work focussed on core descriptions and photography of key lithologic units to define rock unit contacts and reconcile lithofacies variations and/or contacts with geophysical well log data. As clay and organic matter content vary widely through the interval of interest, gamma-ray logs have proven to be most useful in recognizing lithologic contacts. A relatively small proportion of the cores studied have gamma-ray logs associated with them, limiting the ability of geophysical data to assist in regional correlation.

In addition to lithostratigraphic work, core samples will be subjected to other methods of examination, such as oxygen, carbon and sulphur stable isotopic analysis to detect chemostratigraphic trends and/or anomalies that may aid in the recognition of unit boundaries; optical petrography to determine microstructures and mineral content characteristic of specific units; and scanning electron microscopy electron dispersive spectroscopy (SEM–EDS) to examine sedimentary microfabrics and compositional attributes not visible by other methods.

Fossil type and abundance vary significantly through the studied succession and have proven valuable in the recognition of formational-rank boundaries and smaller cycles within the studied interval. Detailed descriptions of the taphonomic and paleoecologic attributes of these strata will aid in the interpretation of oxygen fluctuation, depositional dynamics and faunal patterns that may reveal the underlying processes responsible for the extreme variations in organic matter preservation within this succession. Data collected from this project will ultimately form the basis of a MSc thesis by the senior author that will further explore the possible paleoenvironmental changes recorded in the stratigraphic interval being studied.

It is hoped that this detailed examination of the lithofacies of the Collingwood and Rouge River members, both in subsurface and outcrop will provide descriptive characteristics of the units that will enable correlation of the relatively thin cratonic wedge present in Ontario (Collingwood member and Rouge River member) relative to the much thicker Utica Formation and its coeval formations in other

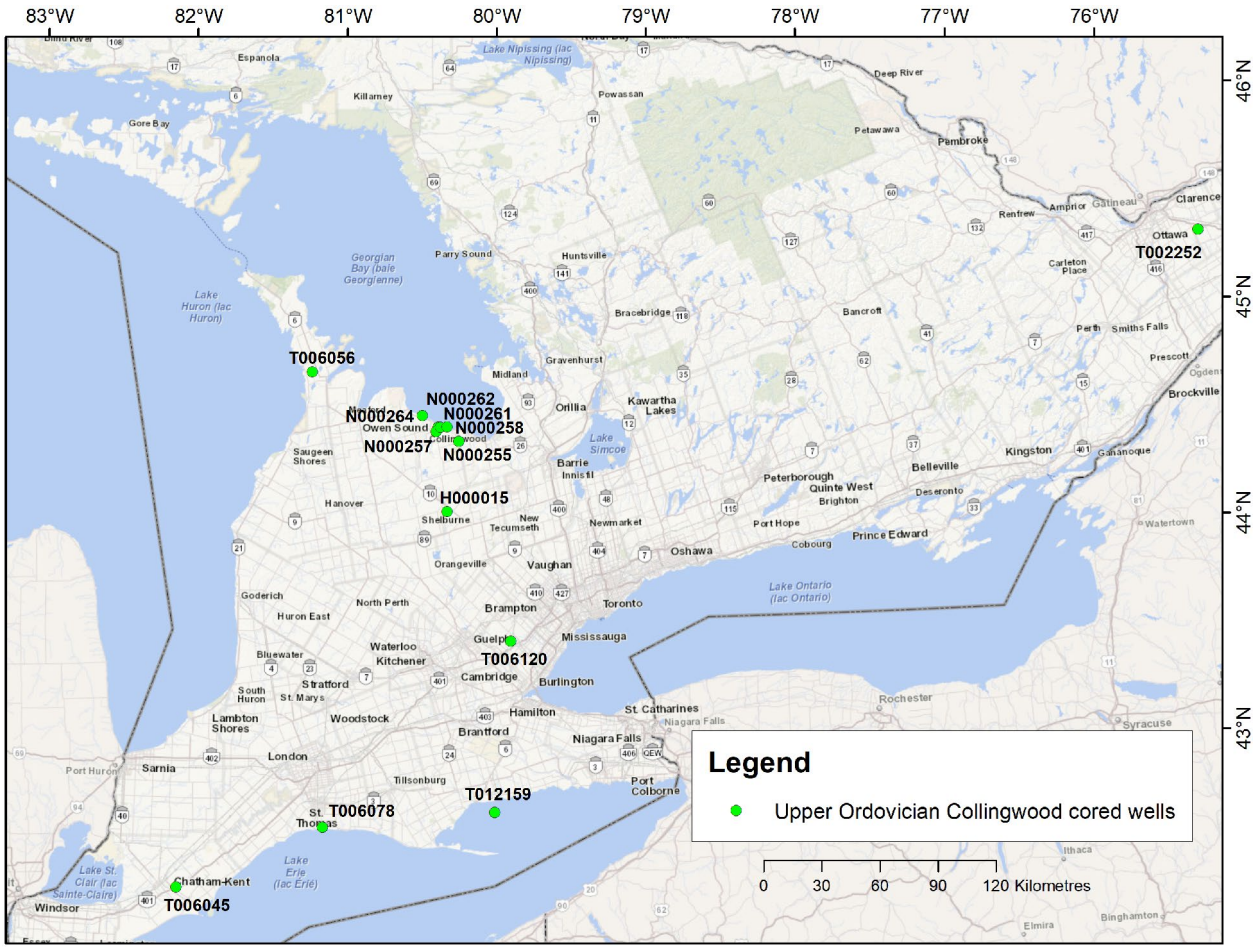


Figure 20.2. Map of southern Ontario showing drill sites corresponding to cores examined during the summer of 2022 (green dots).

jurisdictions (cf. Brett and Baird 2002; Baird and Brett 2002) and build upon the regional characterization of these units by OGS (Béland Otis 2012, 2015a, 2015b). The study will include a sedimentological and sequence stratigraphic approach to assess the interplay between regional tectonic influences relative to sedimentation processes, in addition to carrying out more detailed studies of the organic-rich units (cf. Sweeney 2014; Hamblin 2018).

The organic-rich units are of special interest because Upper Ordovician strata in southern Ontario record drastic climate changes from greenhouse to ice-house climate conditions (Finnegan et al. 2011). Oceanic anoxia during global warming resulted in massive organic carbon burial and accumulation of organic-rich deposits (e.g., black shale), leading to a major depletion of atmospheric CO_2 and global cooling, culminating in the latest Ordovician (Hirnantian: 445.2–443.8 Ma) glaciation and mass extinctions.

ACKNOWLEDGMENTS

This research forms part of a MSc thesis study at the University of Western Ontario by Dan Atasiei. We wish to thank staff at the Oil, Gas and Salt Resources Library in London, Ontario, for their help in compiling key cored wells to be examined in this study. Rhys Paterson and Shuo Sun are thanked for their help concerning how to access the subsurface data available at the core library. The authors also thank Jordan Clark (manager of Oil, Gas and Salt Resources Library) and Ramen Tolo (staff) for assistance with library data, core photography, and handling and sampling specimens.

REFERENCES

Baird, G.C. and Brett, C.E. 2002. Indian Castle Shale: Late synorogenic siliciclastic succession in an evolving Middle to Late Ordovician foreland basin, eastern New York State; Physics and Chemistry of the Earth, v.27, p.203-230.

Béland Otis, C. 2012. Preliminary results: Potential Ordovician shale gas units in southern Ontario; *in* Summary of Field Work and Other Activities, 2012, Ontario Geological Survey, Open File Report 6280, p.29-1 to 29-12.

——— 2015a. Upper Ordovician organic-rich mudstones of southern Ontario: Drilling project results; Ontario Geological Survey, Open File Report 6312, 59p.

——— 2015b. Geological, geochemical and geophysical data from the Ordovician shales drilling program and the regional sampling program, southern Ontario; Ontario Geological Survey, Miscellaneous Release—Data 326.

Brett, C.E. and Baird, G.C. 2002. Revised stratigraphy of the Trenton Group in its type area, central New York: Sedimentology and tectonics of a Middle Ordovician shelf-to-basin succession; Physics and Chemistry of the Earth, v.27, p.231-263.

Brunton, F.R. and Brintnell, C. 2020. Early Silurian sequence stratigraphy and geological controls on karstic bedrock groundwater flow zones, Niagara Escarpment region and the subsurface of southwestern Ontario; Ontario Geological Survey, Groundwater Resources Study 13.

Brunton, F.R., Carter, T., Logan, C., Clark, J., Yeung, K., Fortner, L., Freckelton, C., Sutherland, L. and Russell, H.A.J. 2017. Lithostratigraphic compilation of Phanerozoic bedrock units and 3D geological model of southern Ontario; abstract *in* Regional-scale groundwater geoscience in southern Ontario: An Ontario Geological Survey, Geological Survey of Canada, and Conservation Ontario Geoscientists open house, Guelph, Ontario, March 1–2, 2017, Geological Survey of Canada, Open File 8212, p.3. doi.org/10.4095/299759

Carter, T.R., Brunton, F.R., Clark, J.K., Fortner, L., Freckelton, C., Logan, C.E., Russell, H.A.J., Somers, M., Sutherland, L. and Yeung, K.H. 2019. A three-dimensional geological model of the Paleozoic bedrock of southern Ontario; Ontario Geological Survey, Groundwater Resources Study 19 / Geological Survey of Canada, Open File 8618. doi.org/10.4095/315045

Carter, T.R., Brunton, F.R., Clark, J.K., Fortner, L., Logan, C.E., Russell, H.A.J., Somers, M., Sutherland, L. and Yeung, K.H. 2020. Three-dimensional geological modelling of the Paleozoic bedrock of southern Ontario: Status update; *in* Southern Ontario Groundwater Project 2014–2019; Geological Survey of Canada, Open File 8536, p.7-21. doi.org/10.4095/321079

Carter, T.R., Logan, C.E., Clark, J.K., Russell, H.A.J., Brunton, F.R., Cachunjua, A., D'Arienzo, M., Freckelton, C., Rzyszczak, H., Sun, S. and Yeung, K H. 2021. A three-dimensional geological model of the Paleozoic bedrock of southern Ontario, version 2; Geological Survey of Canada, Open File 8795, 103p. doi.org/10.4095/328297

Finnegan, S., Bergmann, K., Eiler, D.S., Jones, D.A., Eisenman, I., Hughes, N.C., Triparti, A.K. and Fischer, W.W. 2011. The magnitude and duration of Late Ordovician–Early Silurian glaciation; Science, v.331, p.903-906.

Hamblin, A.P. 2018. Stratigraphic architecture, sedimentology, and resource potential of the Upper Ordovician Nottawasaga Group of southwestern Ontario, surface and subsurface: tectonics and sequence stratigraphy in the distal Appalachian Foreland; Geological Survey of Canada, Open File 8153, 86p.

Johnson, M.D., Armstrong, D.K., Sanford, B.V., Telford, P.G. and Rutka, M.A. 1991. Paleozoic and Mesozoic geology of Ontario; Chapter 20 *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 2, p.907-1008.

Kay, M. 1937. Stratigraphy of the Trenton Group; Geological Society of America, Bulletin, v.48, p.233-302.

Liberty, B.A. 1953. Preliminary map, Alliston, Simcoe, York and Dufferin counties, Ontario; Geological Survey of Canada, Paper 53-9, 3p, 1 sheet, scale 1:63 360.

——— 1955. Stratigraphic studies of the Ordovician System in central Ontario; Proceedings of the Geological Association of Canada, v.7, p.139-147.

——— 1964. Upper Ordovician stratigraphy of the Toronto area; *in* Geology of Central Ontario; American Association of Petroleum Geologists–Society of Economic Paleontologists and Mineralogists, Guidebook, p.43-54.

Parks, W.A. 1928. Faunas and stratigraphy of the Ordovician black shales and related rocks in Southern Ontario; Transactions of the Royal Society of Canada, 3rd Series, v.22, section 4, p.39-90.

Rancourt, C. 2009. "Collingwood" strata in south-central Ontario – A petrophysical chemostratigraphic approach to comparison and correlation using geophysical borehole logs; unpublished MSc thesis, University of Toronto, Toronto, Ontario, 65p.

Raymond, P.E. 1914. The Trenton Group in Ontario and Quebec; Geological Survey of Canada, Summary Report 1912, p.342-350.

——— 1916. Expedition to the Baltic provinces of Russia and Scandinavia; Part 1, The correlation of the Ordovician strata of the Baltic Basin with those of eastern North America; Bulletin, Museum of Comparative Zoology, v.56, p.179-187.

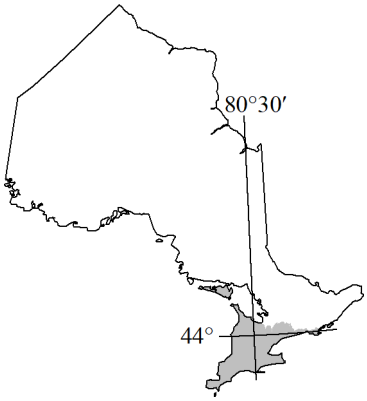
——— 1921. A contribution to the description of the fauna of the Trenton Group; Geological Survey of Canada, Museum Bulletin 31, 67p.

Russell, D.J. and Telford, P.G. 1983. Revisions to the stratigraphy of the Upper Ordovician Collingwood beds of Ontario—A potential oil shale; Canadian Journal of Earth Sciences, v.20, p.1780-1790.

Sanford, B.V. 1961. Subsurface stratigraphy of Ordovician rocks in southwestern Ontario; Geological Survey of Canada, Paper 60-26, 54p.

Sweeney, S.N. 2014. Allostratigraphy of the Upper Ordovician Blue Mountain Formation, southwestern Ontario, Canada; unpublished MSc thesis, The University of Western Ontario, London, Ontario, 301p.

21. Project SO-22-004. Revisiting the Cambrian Stratigraphy of Southwestern Ontario



A.R. Phillips[1], F.R. Brunton[2,1] and K.H. Yeung[2]

[1]Department of Earth Sciences, The University of Western Ontario, London, Ontario N6G 2V4
[2]Earth Resources and Geoscience Mapping Section, Ontario Geological Survey, Sudbury, Ontario P3E 6B5

INTRODUCTION

This project involves an examination of basal Paleozoic sedimentary rocks and underlying variably weathered crystalline basement rocks in key wells across southwestern and southcentral Ontario. These predominantly subsurface Cambrian and Ordovician strata are the least understood and documented part of the Paleozoic succession in southern Ontario (Figure 21.1).

There are more than 20 mostly small, but prolific hydrocarbon reservoirs in the basal siliciclastic-dominated succession of southwestern Ontario (Bailey Geological Services Ltd. and Cochrane 1984; Bailey 2005; Trevail 1990; Dorland 2004; Dorland et al. 2019). Despite this, little is known about the precise age, depositional systems and stratigraphic correlations of the host strata or the formational fluid temperatures, pressures, and porosity and/or permeability values of various rock units. The rock units are generally thought to represent deposition from progressive onlap of Early Paleozoic seas over a broad undulatory Proterozoic basement surface (referred to simplistically as the Algonquin Arch). Subsequently, localized and episodic erosion of these largely unlithified sediments occurred prior to the Ordovician marine transgression(s) and associated onset of carbonate-dominated sedimentation that cover these strata (*see* Hamblin 1998a, 1998b, 2011). Paleotopographic irregularities, and syndepositional and later faulting of the Cambrian and Precambrian basement rocks, appear to have had some local control on the preserved sedimentary rock characteristics and distribution.

A better understanding of the stratigraphy and distribution of Cambrian strata in the subsurface of southern Ontario is important to our general understanding of the Paleozoic history of Ontario and thus has broad and direct relevance to many clients. The relationship of the Cambrian strata to the underlying Proterozoic basement and structures and deep formational fluid characteristics may help us to develop a more robust structural framework for southwestern Ontario that will assist in our understanding of deep regional formational fluid flow, deep disposal of brines and other waste, and other potential deep storage. This project also links directly with other OGS Paleozoic mapping initiatives, including 1) the ongoing three-dimensional (3-D) Paleozoic modelling work using Leapfrog® Works; 2) updates to Paleozoic lithostratigraphic chart and map legend for southern Ontario; and 3) the development of a modern Lexicon of Paleozoic names for southern Ontario (*see* Brunton et al. 2021).

Summary of Field Work and Other Activities, 2022,
Ontario Geological Survey, Open File Report 6390, p.21-1 to 21-7.

© King's Printer for Ontario, 2022

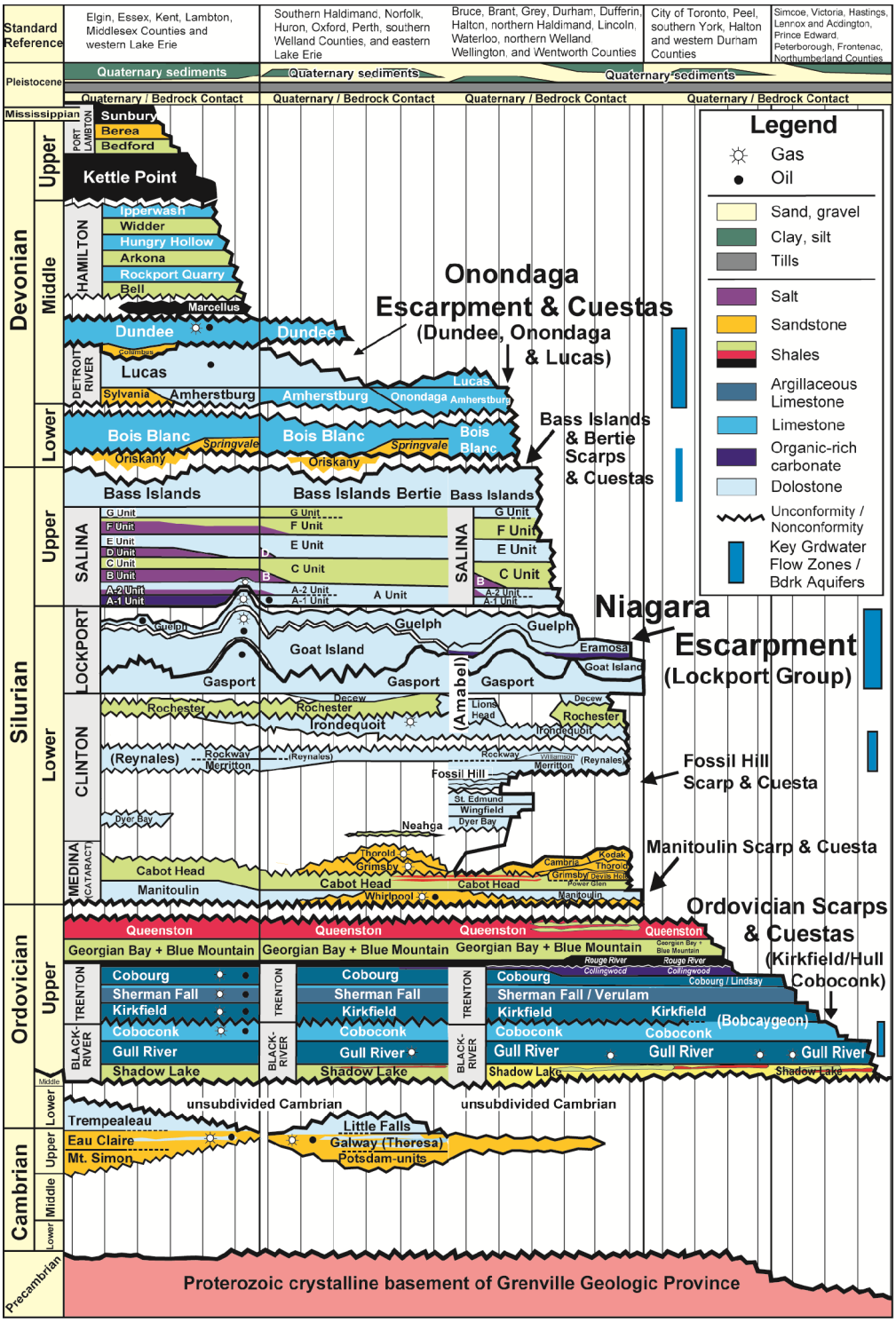


Figure 21.1. Revised terminology of Paleozoic strata for south-central and southwestern Ontario (*modified after* Winder 1961; Beards 1967; Winder and Sanford 1972; Armstrong and Carter 2010; Brunton et al. 2017). Group names are in capitals, members in italics, and abandoned or geographically restricted formation names in brackets. The remaining horizontal black zig-zag lines reflect unconformities, or sequence boundaries. Stepped karstic cuestas and key escarpments are labelled on the right side. The Phanerozoic bedrock topography is depicted by the erosional line (uppermost, thickened, black zig-zag line). The remaining horizontal black zig-zag lines reflect unconformities, or sequence boundaries. The line thicknesses signify inferred missing time intervals (note: Cambrian, Lower to Middle Ordovician and Lower Silurian gaps in sedimentation). The relative thicknesses of rock units are not to scale.

PREVIOUS WORK

The last subsurface project of these basal sedimentary rock units, sponsored by the Ontario Geological Survey, was in the 1980s (Bailey Geological Services Ltd. and Cochrane 1984). That study, based on oil and gas well records, consisted of a resource evaluation for the Cambrian units of southwestern Ontario, structure contour maps for the top of the underlying Proterozoic bedrock and for the top of the overlying Upper Ordovician Shadow Lake Formation, and isopach maps for all units found between these 2 surfaces. As such, that project did not separate out the Cambrian rock units (*see also* Trevail 1990; Carter, Trevail and Easton 1996; Easton and Carter 1991; Geofirma Engineering Ltd. 2012).

The Cambrian–Lower Ordovician strata in the subsurface of southwestern Ontario was last examined in some detail over 60 years ago (Sanford and Quillian 1959). They subdivided the Cambrian succession into 3 formations and applied stratigraphic nomenclature from the Michigan Basin to the west side of southwestern Ontario and Appalachian Foreland Basin nomenclature to the east side (*see also* Hamblin 1998a, 1998b, 2011). Although these terms are now out-of-date, and in some instances, are used elsewhere for much younger strata, they remain in current usage (Armstrong and Carter 2010; Carter et al. 2019; *see* Figure 21.1). Bailey (2005) revisited the Cambrian succession in the subsurface using geophysical logs and drill cuttings. Bailey used Michigan Basin stratigraphic terms and proposed a complex model of repeated cycles of onlap, tilting, uplift and erosion.

Sanford and Quillian (1959) used 130 sets of drill cuttings and drillers logs from approximately 200 wells to map the thickness and distribution of the Cambrian strata in the subsurface of southern Ontario. In the 6 decades since then, more than 900 wells have been drilled into this interval, including several wells under the waters of Lake Erie where the Cambrian section attains a thickness of greater than 175 m. Included in this recent data set are sets of drill cuttings from 900 wells, and drill cores from 129 wells, all of which allow for a better understanding of the stratigraphy and sedimentology of this complex section. These data, in combination with geophysical logs from more than 725 of the wells, also allow for a much better understanding of porosity and permeability trends within this geologic section. This modern data set allows for improved correlations and subdivisions of strata that historically has been lumped together as the “basal beds”.

The Cambrian section, where it is thickest in southwestern Ontario, typically has a basal dolomitic sandstone interval that is overlain by a transitional mixed feldspathic quartz sandstone and carbonate succession, which is often capped by a thick dolostone section that is variably oölitic. Early workers attempted to correlate the drill cuttings from the Cambrian wells in southwestern Ontario to the outcrop belts in Wisconsin or New York (e.g., Cohee 1945, 1947, 1948a, 1948b; Roliff 1954; Sanford and Quillian 1959). The Cambrian section is absent over a large portion of southwestern Ontario known as the Algonquin Arch. In this area, the Proterozoic basement rocks are variably weathered (paleosols) and covered by a varied siliciclastic and mixed carbonate Upper Ordovician (Black River–Trenton) succession.

STUDY AREA AND PRELIMINARY WORK

The proposed subsurface mapping initiative covers southwestern and southcentral Ontario (Figure 21.2). These rocks are largely restricted to the subsurface and only known through hydrocarbon exploration and/or development drilling and deep stratigraphic cores. Twenty key wells were selected from the more than 1225 Cambrian–Precambrian wells in the Oil, Gas and Salt Resources Library database (*see* Figure 21.2; Table 21.1) to provide a representative distribution across southern Ontario. Preference was given to wells with the most complete data, including drill core, drill cuttings and modern geophysical logs. The well databases of adjacent jurisdictions were also reviewed to identify wells with geophysical logs, drill cuttings and core descriptions and/or core analyses. A handful of wells from Michigan, Ohio and New York were selected to make correlations beyond the boundaries of southwestern Ontario.

The 20 key wells selected for this study were drilled between 1962 and 2012. As a result, they have the most complete set of geological data available, including a suite of geophysical logs. Fifteen of the 20 wells have drill core, including 9 that have the entire Cambrian interval cored. Those that do not have core over the entire section have drill cuttings available for examination. Once analyzed, these wells will serve as fenceposts to expand the correlations to the entire database of 1225 wells intersecting the Cambrian in southwestern Ontario.

The staff at the Oil, Gas and Salt Resources Library in London, Ontario, is in the process of photographing the drill cuttings samples and cores of the 20 key wells. This work is mostly done, apart from core from 3 key wells that require a modified set-up, as they are in irregularly sized core boxes. Drill cuttings and cores from all 20 key wells have been logged.

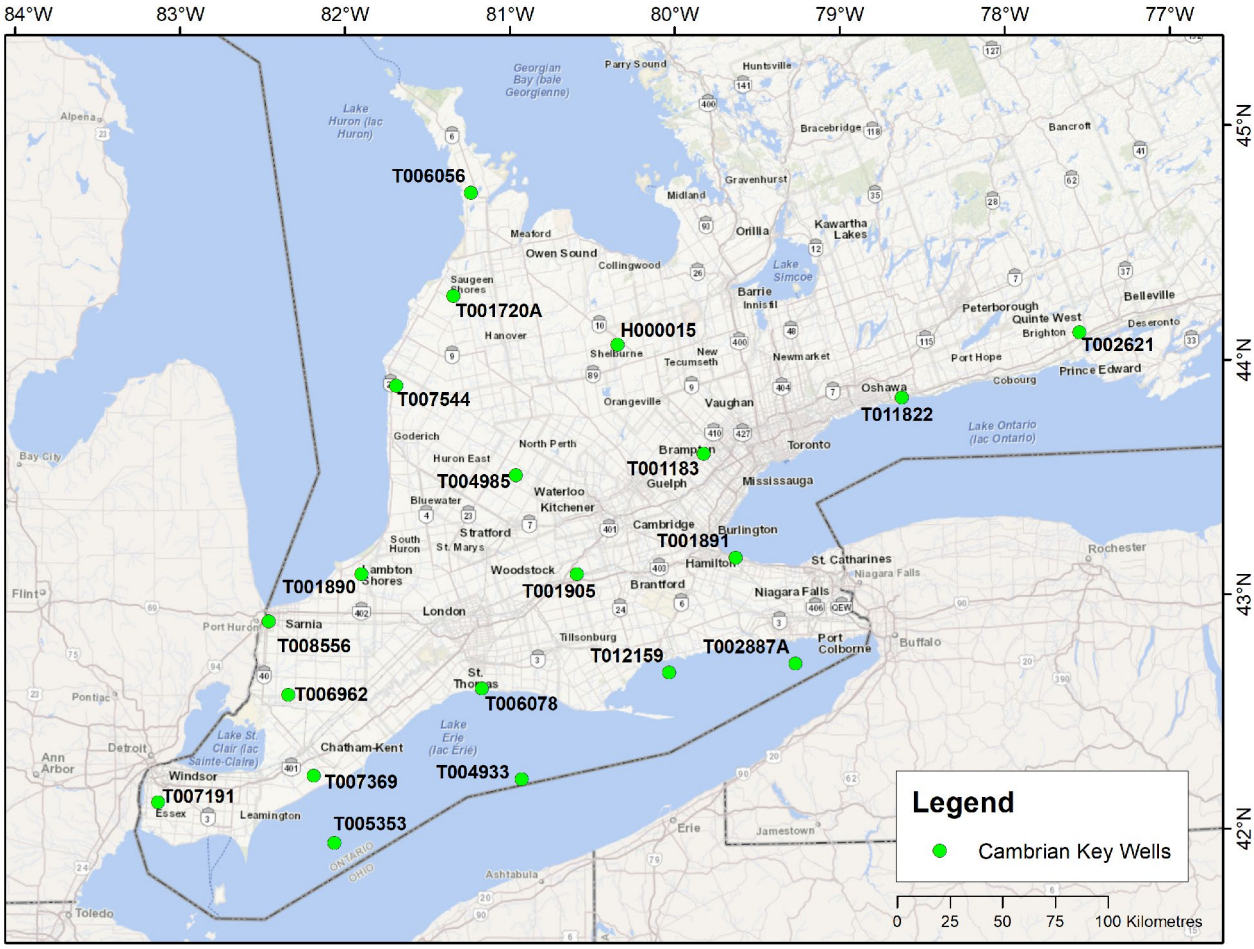


Figure 21.2. Map showing the 20 key Cambrian wells to be examined as part of this study; details on the wells are provided in Table 21.1.

Table 21.1. Key wells selected for subsurface stratigraphic study of the Cambrian succession in southwestern Ontario. Well locations are shown on Figure 21.2 (labelled with Well Licence number). Numbers for core and cuttings in this table correspond to file numbers assigned to drill core boxes and drill cuttings trays at the Oil, Gas, and Salt Research Library in London, Ontario.

Number	Well Licence	County	Township, Location [a]	Well Name	Completion Date	Well Logs [b]	Core Number	Cuttings Number
1	T007191	Essex	Anderdon 2-11-V	Pembina - Maxus	Nov 11, 1987	CNL–LDT, DLL, BHCS, FMS	none	9354-55
2	T007369	Kent	Raleigh 1-17-XIII	Ram/BP No. 5	Aug 20, 1988	CNL–LDT, DLL, BHCS, EPT	986	9508-09
3	T005353	Kent	Lake Erie 284-U-4	Consumers' 13730	July 8, 1980	CNL–FDC, DLL	1030	6921-23
4	T006962	Lambton	Sombra 2-26-V	Ram No. 89	May 14, 1986	CNL–LDT, DLL, BHCS	none	9145-46
5	T008556	Lambton	Sarnia 2-11-RIVIR	Imperial Brine Disposal No. 1	Nov 17, 1997	CN–ZDL, DLL–MLL, BHC-AC	1074	10762-64
6	T001890	Lambton	Bosanquet 3-18-IV	Home-CDR-Union Thedford	Jan 28, 1965	AV, GRD	543	5550-51
7	T006078	Elgin	Yarmouth 3-9-I	OGS 82-3	Mar 11, 1983	TDT, IRT	861	9341-51
8	T004933	Elgin	Lake Erie 184-K-3	Consumers' 13603	July 14, 1979	CNL–FDC, DLL	700	4065-67
9	T012159	Haldimand	Lake Erie 45-E-4C	Dundee East Lake Erie	Sept 11, 2012	CNT–SPeD, AIL, CSL	1130	11774-76
10	T001905	Oxford	Blenheim 3-23-I	Kewanee Gobles No. 40	Dec 14, 1964	GR–N, DENL	150	5530-31
11	T004985	Perth	Elma 2-36-XIV	Petromark et al.	July 20, 1979	GR–N, DENL	none	4068-69
12	T007544	Huron	Ashfield 2-6-XWD	BP No. 1	Jan 6, 1990	CN–ZDL, DLL–MLL, BHC-AC	none	9434-35
13	T001720A	Bruce	Saugeen 2-29-II	BP-Triad (A)	Aug 2, 1964	GR–N, DENL	985	5421-22
14	T006056	Bruce	Albemarle 4-25-IW	OGS 82-4 Wiarton	Nov 22, 1982	GR-SDD, SDN, FEL	862/1103	9352-53
15	H000015	Dufferin	Melancthon 7-251-II	OGS Deep Hole No. 1 - Corbetton	Mar 10, 1982	GR-LSD, SDN, CSS, FEL	1098	9301-06
16	T001183	Peel	Chinguacousy 1-14-VIW	M & M Oil & Gas No. 1	Feb 23, 1962	GR–N	none	3797-98
17	T001891	Wentworth	Saltfleet 2-11-I	Imperial No. 891	Jan 16, 1965	GR–N, DENL	259	5557-58
18	T002887A	Welland	Lake Erie 24-T-3	CPOG Welland No. 2A	Nov 7, 1969	SNP, FDC, BHCS, DILL	648	7559-61
19	T011822	Durham	Darlington 3-12-BFC	St. Mary's Cement DH08-01	Aug 30, 2008	GR–Cond	1121	Core
20	T002621	Hastings	Murray 2-6-III	Consumers' 31758	Nov 26, 1968	GR–N	137	7389-89

[a] *Onshore locations are provided as township, tract, lot and concession. Offshore locations as Lake Erie, block, tract and quadrent.*

[b] *Types of well logs: AIL, Array Induction Log (Weatherford); AV, Acoustic Velocity Log (Welex); BHC-AC, Borehole Compensated Acoustilog (Western Atlas); BHCS, Borehole Compensated Sonic Log (Schlumberger); CN–ZDL, Compensated Neutron–Z-Densilog (Western Atlas); CNL–FDC, Compensated Neutron Log–Formation Density Compensated (Schlumberger); CNL–LDT, Compensated Neutron Log–Litho Density Tool (Schlumberger); CNT–SPeD, Dual Spaced Neutron–Photo Density (Weatherford); CSL, Compensated Sonic (Weatherford); CSS, Compensated Sonic Sonde (BPB Wireline); DENL, Density Log (Welex, Great Guns); DILL, Dual Induction-Laterolog (Schlumberger); DLL, Dual Laterolog (Schlumberger); DLL–MLL, Dual Laterolog–Micro Laterolog (Western Atlas); EPT, Electromagnetic Propagation Tool (Schlumberger); FDC, Compensated Formation Density Log (Schlumberger); FEL, Focused Electric Log (BPB Wireline); FMS, Formation Microscanner (Schlumberger); GR–Cond, Gamma Ray-Apparent Conductivity (Golder Associates); GR–DENL, Density Log (Welex); GR–N, Radioactivity Log, Nuclear Log or Gamma Ray–Neutron (Welex, Birdwell, Great Guns); GR-LSD, Gamma Ray-Long Spaced Density (BPB Wireline); GR-SDD, Gamma Ray-Slim Dual Density (BPB Wireline); GRD, Guard Log (Welex); IRT, Induction Resistivity Tool (Schlumberger); SDN, Slim Dual Neutron (BPB Wireline); SNP, Sidewall Neutron Porosity Log (Schlumberger); TDT, Thermal Decay Time Tool (Schlumberger).*

ACKNOWLEDGMENTS

The initial phase of this study has been supported financially by the Ministry of Natural Resources and Forestry (MNRF) and the Ministry of Mines in collaboration with staff at the Oil, Gas and Salt Resources Library in London, Ontario.

REFERENCES

Armstrong, D.K. and Carter, T.R. 2010. The subsurface Paleozoic stratigraphy of southern Ontario; Ontario Geological Survey, Special Volume 7, 301p.

Bailey, S.M.B. 2005. A comparison of the Cambrian reservoir rocks onlapping the SE and NW sides of the Algonquin Arch in SW Ontario – A regional correlation project; *in* Proceedings, Ontario Petroleum Institute, 44th Annual Meeting, London, Ontario, v.44, Technical Paper 5, 20p.

Bailey Geological Services Ltd. and Cochrane, R.O. 1984. Evaluation of the conventional and potential oil and gas reserves of the Cambrian of Ontario; Ontario Geological Survey, Open File Report 5499, 72p.

Beards, R.J. 1967. Guide to the subsurface Palaeozoic stratigraphy of southern Ontario; Ontario Department of Energy Resources Management, Paper 67-2, 19p.

Brunton, F.R., Béland Otis, C., Hahn, K.E. and Yeung, K.H. 2021. Progress on the development of a new stratigraphic framework for the Paleozoic geology of southern Ontario; *in* Summary of Field Work and Other Activities, 2021, Ontario Geological Survey, Open File Report 6380, p.16-1 to 16.9.

Brunton, F.R., Carter, T., Logan, C., Clark, J., Yeung, K., Fortner, L., Freckelton, C., Sutherland, L. and Russell, H.A.J. 2017. Lithostratigraphic compilation of Phanerozoic bedrock units and 3D geological model of southern Ontario; *in* Regional-Scale Groundwater Geoscience in Southern Ontario: An Ontario Geological Survey, Geological Survey of Canada, and Conservation Ontario Open House; Geological Survey of Canada, Open File 8212, p.3. doi.org/10.4095/299750

Carter, T.R., Brunton, F.R., Clark, J.K., Fortner, L., Freckelton, C., Logan, C.E., Russell, H.A.J., Somers, M., Sutherland, L. and Yeung, K.H. 2019. A three-dimensional geological model of the Paleozoic bedrock of southern Ontario; report [PDF] *in* Ontario Geological Survey, Groundwater Resources Study 19 / Geological Survey of Canada, Open File 8618, 56p.

Carter, T.R., Trevail, R.A. and Easton, M. 1996. Basement controls on some hydrocarbon traps in southern Ontario, Canada; *in* Basement and basins of eastern North America, Geological Society of America, Special Paper 308, p.95-107.

Cohee, G.V. 1945. Stratigraphy of Lower Ordovician and Cambrian rocks in the Michigan Basin; United States Geological Survey, Oil and Gas Investigations, Preliminary Chart no.9.

——— 1947. Lithology and thickness of the Traverse Group in the Michigan Basin; United States Geological Survey, Oil and Gas Investigations, Preliminary Chart no.28.

——— 1948a. Thickness and lithology of Upper Ordovician and Lower and Middle Silurian rocks in the Michigan Basin; United States Geological Survey, Oil and Gas Investigations, Preliminary Chart no.33.

——— 1948b. Cambrian and Ordovician rocks in Michigan Basin and adjoining areas; American Association of Petroleum Geologists Bulletin, v.32, p.1417-1448.

Dorland, M. 2004. Cambrian reservoirs of southwestern Ontario; Ontario Oil & Gas Magazine, 2004 Edition, Ontario Petroleum Institute, London, Ontario, p.20-22.

Dorland, M., Colquhoun, I., Carter, T.R., Phillips, A., Fortner, L., Clark, J. and Hamilton, D. 2019. Ontario Oil and Gas Plays 2. Cambrian and Ordovician conventional plays; Ontario Oil & Gas Magazine, 2019 Edition, Ontario Petroleum Institute, London, Ontario, p.34-41.

Easton, R.M. and Carter, T.R. 1991. Extension of Grenville basement beneath southwestern Ontario; Ontario Geological Survey, Open File Map 162, scale 1:1 013 760.

Geofirma Engineering Ltd. 2012. Geoscientific characterization of shaft investigation boreholes DGR-7 and DGR-8; Nuclear Waste Management Organization (NWMO), Toronto, Ontario, NWMO Report DGR-TR-2012-01, 127p.

Hamblin, A.P. 1998a. Upper Cambrian strata of southwestern Ontario: Summary of literature; Geological Survey of Canada, Open File Report 3663, 10p.

——— 1998b. Upper Cambrian and Lower (Middle?) Ordovician sandstones of the Ottawa Embayment: Summary of literature; Geological Survey of Canada, Open File 3670, 10p.

——— 2011. Detailed outcrop and core measured sections of Upper Cambrian and Middle Ordovician sandstones (and associated facies), southwestern Ontario; Geological Survey of Canada, Open File 6856, 41p.

Roliff, W.A. 1954. The pre-Middle Ordovician rocks of southwestern Ontario; Proceedings of the Geological Association of Canada, v.6, part II, p.103-109.

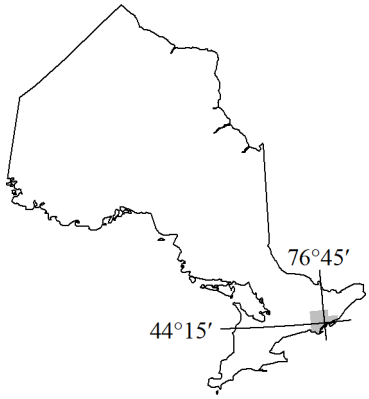
Sanford, B.V. and Quillian, R.G. 1959. Subsurface stratigraphy of Upper Cambrian rocks in southwestern Ontario; Geological Survey of Canada, Paper 58-12, 33p.

Trevail, R.A. 1990. Cambro–Ordovician shallow water sediments, London area, southwestern Ontario; *in* Subsurface geology of southwestern Ontario: A core workshop; American Association of Petroleum Geologists, 1990 Eastern Section Meeting, London, Ontario, p.29-50.

Winder, C.G. 1961. Lexicon of Paleozoic names in southwestern Ontario; University of Toronto Press, Toronto, Ontario, 121p.

Winder, C.G. and Sanford, B.V. 1972. Stratigraphy and paleontology of the Paleozoic rocks of southern Ontario; 24th International Geological Congress, Montreal, Quebec, Excursion A45-C45, 73p.

22. Project SO-22-001. Paleozoic Geology of the Kingston Area, Eastern Ontario



K.E. Hahn[1]

[1]Earth Resources and Geoscience Mapping Section, Ontario Geological Survey

INTRODUCTION

In 2022, the Ontario Geological Survey (OGS) initiated a multi-year mapping project focussed on the Paleozoic geology of eastern south-central Ontario (Figure 22.1). This work builds upon current mapping in eastern Ontario, which, over the past few years, has suggested several revisions to the Ordovician stratigraphic nomenclature in eastern Ontario (Béland Otis 2017, 2018, 2019). These mapping projects are contributing to a formalized revision to the Paleozoic legend that the OGS is currently undertaking (Brunton et al. 2021).

The study area encompasses the region from Belleville to Gananoque and is bounded by Lake Ontario to the south and the Precambrian–Paleozoic unconformity in the north (*see* Figure 22.1). The area is represented by 10 National Topographic System (NTS) maps and was last mapped by the OGS in the 1980s (Carson 1981a, 1981b, 1981c; Carson 1982a, 1982b). No detailed summary report exists to accompany these maps and, since then, only minor revisions to the maps have been completed during publication of the seamless Paleozoic geology map of southern Ontario (Armstrong and Dodge 2007). Prior to OGS mapping, the area was mapped by Liberty in the 1960s (Liberty 1971) and the stratigraphic nomenclature in use by the OGS for this part of Ontario is based on the work of Liberty (1969).

The Paleozoic bedrock near Kingston has been the subject of many academic studies and thesis projects (e.g., McFarlane 1992; Salad Hersi and Dix 1999; Lowe et al. 2017; James, Narbonne and Armstrong 2020). The bulk of these studies employ stratigraphic nomenclature that is not in use by the OGS, but rather includes nomenclature that predates the work of Liberty or is more commonly used in New York State (Figure 22.2). This study contributes to the ongoing OGS focus to update the Paleozoic legend at formational rank for all of southern Ontario (Brunton et al. 2021).

There are 3 goals that this project aims to address:

1. reconcile the nomenclature and stratigraphic framework of the Kingston area with proposed revisions to the OGS Paleozoic legend review (*see* Brunton et al. 2021; Béland Otis 2017, 2018, 2019)
2. establish a regional chemostratigraphic profile using stable carbon and oxygen isotopes to assist in regional correlations
3. update the mapped formational-rank contacts between the various Paleozoic units as well as along the Precambrian–Paleozoic unconformity.

The Ordovician sedimentary rocks of eastern south-central Ontario are important sources for aggregate and groundwater and the updated mapping will contribute to better land-use planning in the region. Anticipated products of this project include 10 geological maps, at a scale of 1:50 000, and an Open File Report.

Summary of Field Work and Other Activities, 2022,
Ontario Geological Survey, Open File Report 6390, p.22-1 to 22-10.

© King's Printer for Ontario, 2022

2022 FIELD WORK

The 2022 field season included reconnaissance work between Gananoque and Napanee. A total of 119 field stations were selected to be stratigraphically representative of the study area, and a total of 13 cores, housed at the Southern Ontario Resident Geologist Office, in Tweed, were logged and sampled (*see* Figure 22.1; Table 22.1). Outcrops and cores were sampled for whole-rock geochemical analysis and thin sections for general lithostratigraphic characterization (total of 253 samples); selected cores were sampled at a regular 1 m vertical spacing for stable carbon and oxygen isotope analysis (total of 71 samples).

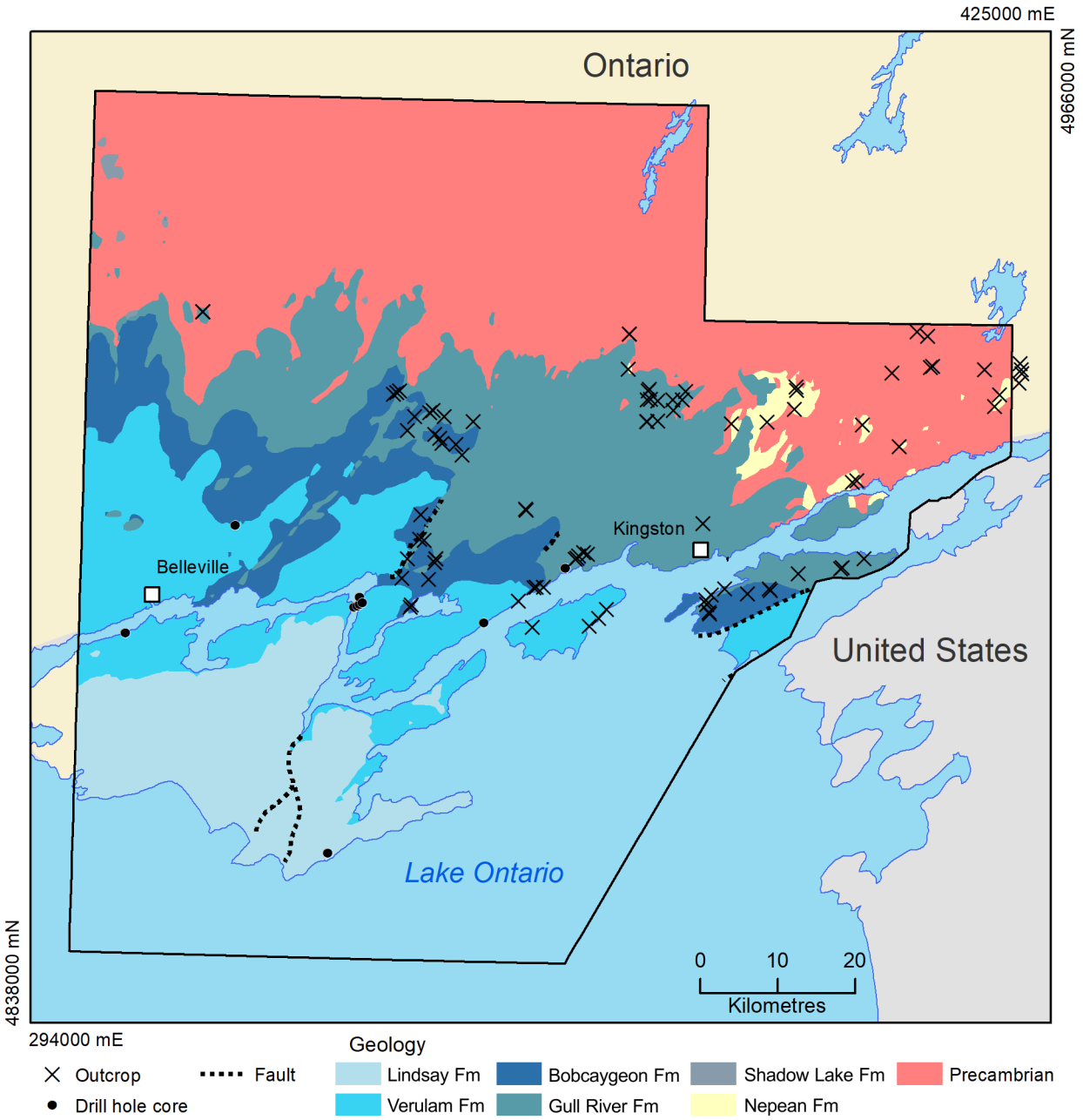


Figure 22.1. General bedrock geology (*from* Armstrong and Dodge 2007; *modified from* Carson 1981a, 1981b, 1981c, 1982a,1982b) of the study area showing the locations of 2022 mapped outcrop stations and drill cores logged. Universal Transverse Mercator (UTM) co-ordinates provided in North American Datum 1983 (NAD83) in Zone 18. Abbreviation: Fm, Formation.

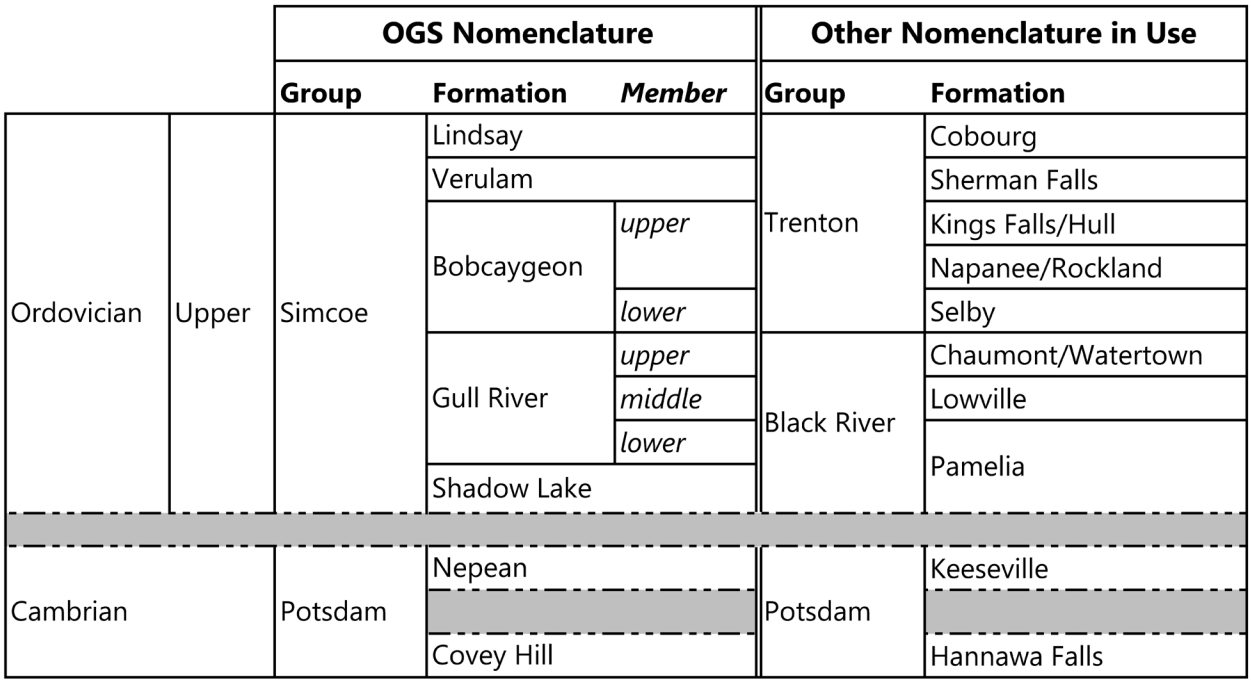


Figure 22.2. Terminology of Paleozoic strata in eastern south-central Ontario. Other nomenclature in use is specific to the Kingston area (from compilation of McFarlane 1992, and references therein); a more extensive review of other terminologies in use in the Ottawa graben can be found in Béland Otis (2017). It is currently unknown how much of the proposed new terminology in the Ottawa graben can be extended to the Kingston area. Grey areas outlined by dashed lines represent disconformities.

Table 22.1. Cores examined during the summer of 2022.

Station ID	Core ID	Dip (°)	Depth (m)	Easting [a] (m)	Northing [a] (m)	Top Stratigraphic Unit [b]
2022-HAH-0001	TW0330	71	59.4	332100	4859550	Lindsay Fm
2022-HAH-0002	TW0367	90	37.2	335500	4891300	Verulam Fm
2022-HAH-0003	TW0373	90	103.1	352250	4889250	Verulam Fm
2022-HAH-0004	TW0406	35	68.4	336550	4891900	Verulam Fm
2022-HAH-0005	TW0476	90	20.2	336250	4892550	Verulam Fm
2022-HAH-0006	TW0477	90	31.7	336250	4891450	Verulam Fm
2022-HAH-0008	TW0478	90	33.4	335900	4891450	Verulam Fm
2022-HAH-0128	TW1264	90	4.9	362750	4896300	Gull River Fm
2022-HAH-0129	TW1265	90	4.6	362750	4896300	Gull River Fm
2022-HAH-0130	TW1266	90	4.9	362750	4896300	Gull River Fm
2022-HAH-0131	TW1267	90	4.9	362750	4896300	Gull River Fm
2022-HAH-0132	TW1289	90	34.6	306006	4888000	Verulam Fm
2022-HAH-0133	TW2569	45	78	320192	4902079	Verulam Fm

[a] *Locations are provided as Universal Transverse Mercator (UTM) co-ordinates using North American Datum 1927 (NAD27) in Zone 18.*
[b] ***Abbreviation:*** *Fm = Formation.*

Paleozoic Stratigraphy of Eastern South-Central Ontario

The Paleozoic sedimentary rocks through the study area onlap Precambrian basement of the Grenville Province. The Precambrian basement forms an undulatory surface with local bedrock highs that, in places, form inliers in the Paleozoic rocks. The Paleozoic rocks form a broadly east-trending outcrop belt, with the oldest rocks exposed to the North, near the Precambrian–Paleozoic unconformity. The region is underlain primarily by limestone and dolostone Ordovician and minor Cambrian sedimentary rocks. The sedimentary package was once part of the St. Lawrence Platform and had been continuous to eastern Ontario, but it is now bounded from eastern Ontario by the present-day positive structural element of the Frontenac Arch. Sediments dip shallowly southward and progressively young and thicken to the south.

The siliciclastic sedimentary rocks of the Potsdam Group are the oldest Paleozoic strata in the study area. These rocks crop out mainly in the easternmost part of the study area, most commonly as outliers sitting unconformably on the Precambrian basement rock (Photo 22.1A). Current OGS maps identify 2 formations in the Potsdam Group: the Covey Hill Formation and the overlying Nepean Formation. In the project area, only the Nepean Formation is currently shown on existing maps (Armstrong and Dodge 2007; Carson 1982a). Recent work in the Ottawa area (e.g., Béland Otis 2017) suggests following a tripartite subdivision proposed by Lowe et al. (2017) that includes the Ausable, Hannawa Falls and Keeseville formations. In the existing nomenclature, the Ausable and Hannawa Falls formations correlate with the Covey Hill Formation, whereas the Keeseville Formation correlates with the Nepean Formation. A more detailed overview can be found in Béland Otis (2017, 2018, 2019). In the study area, Lowe et al. (2017) identified Hannawa Falls and Keeseville formational outcrops. During the 2022 field season, several outcrops of the Potsdam Group were examined. Two outcrops of red, boulder and cobble conglomerate beds several metres thick were observed (Photo 22.1B). These outcrops may be related to the Covey Hill Formation (not shown on existing maps for the area) or, alternatively, could be considered Ausable Formation or Hannawa Falls Formation (Lowe et al. 2017). Further work is required to better classify these outcrops and to determine their extent. In the easternmost part of the study area, several outcrops of fine sand grade, white to tan quartz arenites were observed as outliers on the Precambrian basement. Typical sedimentary structures include laminated beds, cross-beds and some vertical burrows. In some places, sandstones displayed red liesegang banding and enigmatic vertical structures (Photo 22.1C). These outcrops are mapped as Nepean Formation (Carson 1982a), but alternatively could be placed within the Keeseville Formation of Lowe et al. (2017).

The Simcoe Group stratigraphically overlies the Potsdam Group (although this relationship was not observed in the study area), and it includes all of the Ordovician units in south-central Ontario. In ascending order, Simcoe Group units in the study area include the Shadow Lake, Gull River, Bobcaygeon, Verulam and Lindsay formations.

The Shadow Lake Formation crops out most commonly near the Precambrian–Paleozoic unconformity and is present in all the observed drill cores in the study area that extend to basement. It is on average 6 m thick, but can display significant local variation, dependant on the basement topography. The Shadow Lake Formation is composed of red and green sandstones, siltstones and shale and may include clasts of the underlying basement or large quartz clasts. Where present directly on Precambrian basement, it fills in underlying basement paleotopography and joints, and commonly includes many fragments of underlying basement. Upsection, the Shadow Lake Formation becomes siltier and may contain burrows. In no place was the Shadow Lake Formation observed in contact with the Potsdam Group. The age of the Shadow Lake Formation is difficult to determine because of a lack of biostratigraphically useful faunas and the absence of bentonites. It is further complicated by the fact that, through much of southern Ontario, it simply represents whatever siliciclastic material is sitting directly on the Precambrian bedrock surface. In eastern Ontario, the Shadow Lake Formation has been included as part of the Pamelia Formation (e.g., McFarlane 1992; Salad Hersi and Dix 1999). The upper contact with the Gull River

Formation is gradational and generally marked at the first occurrence of a thick carbonate bed (Liberty 1969, 1971; Carson 1981a, 1981b, 1982a, 1982b, 1982c).

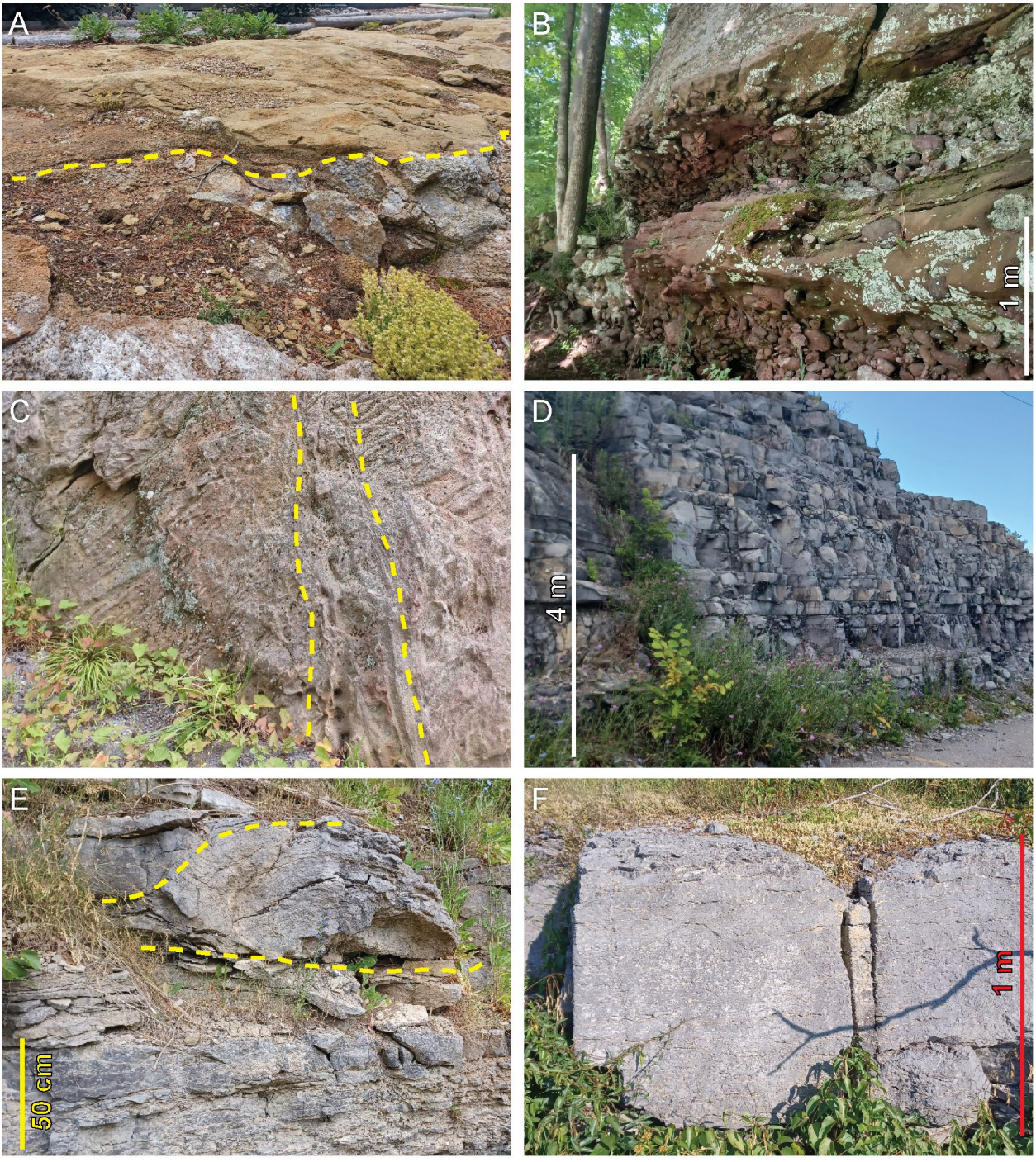


Photo 22.1. Representative photos of rocks of the Potsdam and Simcoe groups from the 2022 field season. **A)** Outcrop photo of the presumed Potsdam Group sandstone in unconformable contact with the underlying Precambrian bedrock. Photo is approximately 1 m wide in the foreground. **B)** Interbedded cobble and boulder conglomerate with sandstone in the Potsdam Group. **C)** Enigmatic vertical structure (between yellow dashed lines; photo approximately 1 m high) in the Potsdam Group. **D)** Tabular and medium-bedded limestone and dolostone of the lower Gull River Formation (Pamelia Formation). **E)** Microbial mounds in the upper Gull River Formation (Lowville Formation). **F)** Thick-bedded, massive wackestone to packstone of the upper part of the Gull River Formation on Wolfe Island (Chaumont Formation?).

The lower and middle members of the Gull River Formation (Pamelia Formation; e.g., McFarlane 1992) crop out throughout the study area, particularly in the northern and eastern parts of the study area. The lower member is generally a dark grey-brown, finely crystalline limestone, whereas the middle member is typified by thin- to medium-bedded, interbedded limestone, dolostone and dolomitic limestone, ranging in colour from pale grey to whitish grey (limestone), to pale green or pale yellow (dolomitic limestone and dolostone; Photo 22.1D). Varying amounts of rounded, frosted, quartz sand or silt can be present in beds through the entire unit. In general, beds are tabular. A variety of sedimentary features are present throughout both members including intraclastic horizons, ooid beds, mud cracks, microbial lamination, vertical and horizontal burrows, salt hoppers, dissolved-out gypsum laths, pink calcite-filled vugs and bird's-eye texture. The unit contains a restricted marine fauna of predominantly molluscs, ostracods and arthropods, with some occurrences of stromatolites and rare crinoids. The top of the last dolostone bed is usually placed as the upper contact of the lower Gull River Formation in south-central Ontario (e.g., Armstrong 2000) and in the Ottawa graben (Williams 1991). Given this definition, the combined lower and middle members of the Gull River Formation in the Kingston area are equivalent to the lower member of the Gull River Formation in the Ottawa graben, and of south-central Ontario. This unit is also referred to as the Pamelia Formation (e.g., McFarlane 1992; Salad Hersi and Dix 1999).

The upper Gull River Formation (Lowville Formation) consists of medium- to thick-bedded, dark grey to dark brown tabular limestone. Several distinct lithofacies are present in the Kingston area, including beds (up to 1 m thick) of bivalve floatstone with ooid packstone to grainstone matrix, beds of wackestone to packstone with abundant fragments of *Tetradium* corals, angular and chaotic intraclast-bearing beds, and at least 3 horizons where metre-scale stromatolite bioherms have formed (Photo 22.1E). Locally, thick units of shaly limestone are also present. The upper Gull River Formation of the Kingston area is also referred to as the Lowville Formation (e.g., McFarlane 1992; James, Narbonne and Armstrong 2020).

Rocks currently mapped as upper Gull River Formation and cropping out on parts of Wolfe Island (Liberty 1971; Carson 1982a) and at the Highway 401 Camden East exit, also mapped as unit D of the Gull River Formation by Liberty (1971), have also been described as the Chaumont Formation (McFarlane 1992; James, Narbonne and Armstrong 2020). These thick limestone beds are finely crystalline limestone that is dark brown on fresh surfaces and weathers pale grey (Photo 22.1F). This unit is fossil rich and contains abundant cephalopods, bivalves, *Tetradium*, crinoids and some brachiopods. Well-developed horizontal burrows are common on bedding planes at the Camden East outcrop. In eastern Ontario, the rocks that some authors (e.g., Salad Hersi and Dix 1999; Oruche, Dix and Kamo 2018) refer to as Chaumont Formation occupy the stratigraphic position of lower Bobcaygeon Formation, rather than uppermost Gull River Formation. Considerable confusion exists regarding whether the Chaumont Formation (or unit D of the upper Gull River Formation) is traceable to the west. Liberty (1971) described it as pinching out near Napanee, with the "Moore Hill Beds" appearing westward into the Carden plain. The Moore Hill Formation (termed "Moore Hill Beds" by some authors), originally defined by Okulitch (1939), was suggested as a local term for the beds lying between the Gull River Formation and the Coboconk Formation (Bobcaygeon Formation) above. Okulitch (1939) found these beds to be distinctive faunally from the underlying Gull River Formation. The "Moore Hill Beds" contain Chaumont Formation fauna, but have previously been correlated to Liberty's member C of the Gull River Formation (Liberty 1971), so following this description, they are either stratigraphically lower than the Chaumont Formation, or they are approximately equivalent. Alternatively, the "Moore Hill Beds" have been placed within the lowest part of the Bobcaygeon Formation (in the same stratigraphic position as the Chaumont Formation of eastern Ontario; Armstrong 2000). This part of the stratigraphic package is named the Coboconk Formation in the subsurface of south-central and southwestern Ontario (e.g., Johnston 1912; Sanford 1993; Armstrong and Carter 2010). The similarity in descriptions and fauna, as well as occupying a similar position stratigraphically, makes re-evaluating the use of these terminologies difficult and forms a component of this project, as well as ongoing revisions to the Paleozoic legend (Brunton et al. 2021).

From the Ottawa graben to south-central Ontario, the Bobcaygeon Formation represents the lithologic unit that lies stratigraphically between the more distinctive Gull River and Verulam formations. In the map area, the Bobcaygeon Formation is presently subdivided into 2 members; however, elsewhere in Ontario, its divided into 3 members (Liberty 1969; Williams 1991; Armstrong 2000). Previous work in the map area has identified this unit as ranging from 6 to 9 m thick. Descriptions of the Bobcaygeon Formation from Kingston to Belleville are vague, and somewhat inconsistent with descriptions of it to the west (Lake Simcoe area) and the east (Ottawa region). General features of the Bobcaygeon Formation that help distinguish it from the units below include a change in fauna from mostly restricted marine fauna in the Gull River Formation to an increase in crinoids, brachiopods and bryozoans, indicating a change to more open marine conditions. There is also a gradual increase in shale content, as well as common hardground surfaces and storm beds (Photo 22.2A). Outcrops in the map area are sparse, and most commonly are exposed as bedding plane surfaces where identifiable features are limited. Below is an attempt to correlate the members of the Bobcaygeon Formation near Kingston to those in eastern Ontario and south-central Ontario.

The lower member is typically made of fine- to medium-crystalline, pale to dark brown and grey limestone, interbedded with calcarenites (Carson 1982b). In general, this unit is more resistant to weathering than the upper unit. Outcrops of this unit are sparse and are generally limited to bedding plane surfaces.

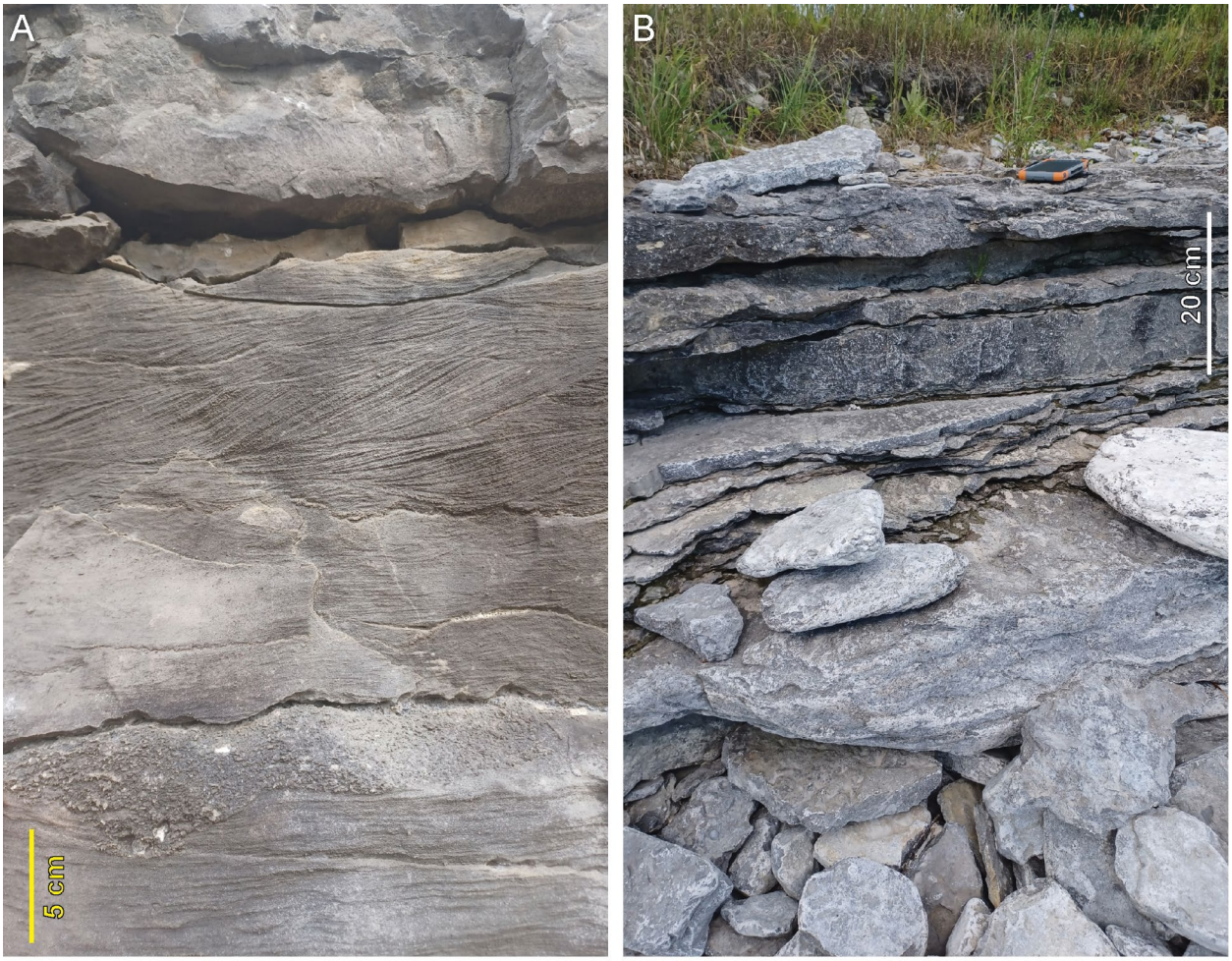


Photo 22.2. Representative outcrop photos of the upper part of the Simcoe Group from the 2022 field season. **A)** Cross-bedded grainstone and scoured surface, interpreted to be storm beds, in the Bobcaygeon Formation. **B)** Fossiliferous packstone and shale (preferentially weathered out) interbeds of the Verulam Formation.

In the few instances where this unit forms vertical outcrops, it is a thin- to medium-bedded, dark bluish grey limestone of interbedded wackestone and packstone storm beds. In the map area, this unit has also been referred to as the Napanee Formation (e.g., McFarlane 1992). Future work will involve defining how it correlates to similar parts of the Bobcaygeon Formation to the east (L'Orignal Formation?: e.g., Béland Otis 2019; Oruche, Dix and Kamo 2018) and the west (Kirkfield Formation?: e.g., Paton and Brett 2020).

The upper member is described similarly to the lower member: it comprises medium to dark grey or brown grey, finely crystalline limestone with interbeds of calcarenites and shale seams. The key differences are the increase in shale content and a general pattern of thinner bedding. According to Carson (1982b), the contact is gradational between the 2 members. As mapped, this unit is up to 3 m thick in the study area. It is currently unknown how this upper member correlates to the east (Rockland and Hull formations?: Oruche, Dix and Kamo 2018) and the west (Kirkfield Formation?: Paton and Brett 2020).

The Verulam Formation crops out on the south side of Wolfe Island and Bathurst Island, as well as the western part of the study area (not examined during this field season). In general, the Verulam Formation is described as interbedded wackestone, packstone and grainstone beds between 5 and 25 cm thick, with shale seams. In outcrop, shale-rich beds display recessive weathering, and outcrops tend to be quite rubbly (Photo 22.2B). The most common fauna in the Verulam Formation include brachiopods, bryozoans and crinoids. The overlying Lindsay Formation was not observed during this field season.

FUTURE WORK

Detailed field work in the areas represented by each NTS map will be undertaken over the next 3 years. Additionally, core logging of drill cores from the study area that are stored at the Oil, Gas and Salt Resources Library (London, Ontario) will be undertaken. Next steps of this project include compiling historical and digital data from water well records, geotechnical boreholes, and any other data that has been acquired since the previously published version of these maps. Stable carbon and oxygen isotope profiles through stratigraphic columns are increasingly being used in regional mapping for correlation purposes. Stable carbon isotope profiles can be used to correlate stratigraphic sections locally and regionally and, when depositional conditions were right, can be used to correlate stratigraphic sections to a global oceanic signal. When used in conjunction with biostratigraphy and/or age control, chemostratigraphy can help constraint the age of sedimentary rocks. If bentonite beds are found during this study, they can be used to tie the chemostratigraphic profiles to an absolute age. Stable isotope data can also be used to help identify disconformity surfaces and diagenetic alteration, and to assist in making tectonostratigraphic interpretations to refine a stratigraphic framework in a basin. The results of several recent studies on the chemostratigraphy of the Simcoe and Ottawa groups (Paton and Brett 2019; Oruche, Dix and Kamo 2018) indicate that there are several positive carbon excursions that could prove useful for correlation purposes. It is the hope that several of the cores sampled during this field season for carbon and oxygen isotopic analyses will assist in regional correlations.

ACKNOWLEDGMENTS

The author wishes to acknowledge the assistance of William Scott (Laurentian University) during the field season, as well as Laura Mancini, Mateo Dorado-Troughton and Harry Craig from the Southern Ontario Resident Geologist office. Kei Yeung (GIS technical help) and Julien Bonin (drafting figures) are gratefully acknowledged for providing help with preparing maps and figures. The author would like to thank the Algonquins of Pikwakanagan First Nation, Alderville First Nation, Curve Lake First Nation, Hiawatha First Nation, Mississaugas of Scugog Island First Nation, Mohawks of the Akwesasne and the Mohawks of the Bay of Quinte for allowing the Ontario Geological Survey to map their traditional land use area. Finally, Catherine Béland Otis and Frank Brunton are thanked for many lively discussions, technical expertise, and for reviewing this report.

REFERENCES

Armstrong, D.K. 2000. Paleozoic geology of the northern Lake Simcoe area, south-central Ontario; Ontario Geological Survey, Open File Report 6011, 43p.

Armstrong, D.K. and Carter, T.R. 2010. The subsurface Paleozoic stratigraphy of southern Ontario; Ontario Geological Survey, Special Volume 7, 301p.

Armstrong, D.K. and Dodge, J.E.P. 2007. Paleozoic geology of southern Ontario; Ontario Geological Survey, Miscellaneous Release—Data 219.

Béland Otis, C. 2017. Paleozoic geology of eastern Ontario; *in* Summary of Field Work and Other Activities, 2017, Ontario Geological Survey, Open File Report 6333, p.22-1 to 22-11.

——— 2018. Paleozoic geology of eastern Ontario: Ottawa area; *in* Summary of Field Work and Other Activities, 2018, Ontario Geological Survey, Open File Report 6350, p.22-1 to 22-10.

——— 2019. Paleozoic geology of eastern Ontario: Arnprior–Quyon area; *in* Summary of Field Work and Other Activities, 2019, Ontario Geological Survey, Open File Report 6360, p.20-1 to 24-10.

Brunton, F.R., Béland Otis, C., Hahn, K.E. and Yeung K. 2021. Progress on the development of a new stratigraphic framework for the Paleozoic geology of southern Ontario; *in* Summary of Field Work and Other Activities, 2021, Ontario Geological Survey, Open File Report 6380, p.16-1 to 16-9.

Carson, D.M. 1981a. Paleozoic geology of the Kaladar–Tweed area, southern Ontario; Ontario Geological Survey, Preliminary Map P.2411, scale 1:50 000.

——— 1981b. Paleozoic geology of the Tichborne–Sydenham area, southern Ontario; Ontario Geological Survey, Preliminary Map P.2413, scale 1:50 000.

——— 1981c. Paleozoic geology of the Belleville–Willington area, southern Ontario; Ontario Geological Survey, Preliminary Map P.2412, scale 1:50 000.

——— 1982a. Paleozoic geology of the Gananoque–Wolfe Island area, southern Ontario; Ontario Geological Survey, Preliminary Map P.2496, scale 1:50 000.

——— 1982b. Paleozoic geology of the Bath–Yorkshire Island area, southern Ontario; Ontario Geological Survey, Preliminary Map P.2497, scale 1:50 000.

James, N.P., Narbonne, G.M. and Armstrong, A.K.R. 2020. Aragonite depositional facies in a Late Ordovician calcite sea, eastern Laurentia; Sedimentology, v.67, p.3513-3532.

Johnston, W.A. 1912. Geology of the Lake Simcoe area, Ontario: Brechin and Kirkfield sheets; Geological Survey of Canada, Summary Report, 1911, p.253-261.

Liberty, B.A. 1969. Paleozoic geology of the Lake Simcoe area, Ontario; Geological Survey of Canada, Memoir 355, 201p.

——— 1971. Paleozoic geology of the Wolfe Island, Bath, Sydenham, and Gananoque map-areas, Ontario; Geological Survey of Canada, Paper 70-35, 12p., 4 maps.

Lowe, D.G., Arnott, R.W.C., Nowlan, G.S. and McCracken, A.D. 2017. Lithostratigraphic and allostratigraphic framework of the Cambrian–Ordovician Potsdam Group and correlations across Early Paleozoic southern Laurentia; Canadian Journal of Earth Sciences, v.54, p.550-585.

McFarlane, R.B. 1992. Stratigraphy, paleoenvironmental interpretation, and sequences of the Middle Ordovician Black River Group, Kingston, Ontario, Canada; unpublished PhD thesis, Queen's University, Kingston, Ontario, 167p.

Okulitch, V.J. 1939. The Ordovician section at Coboconk, Ontario; Royal Canadian Institute, Transactions, v.33, p.319-339.

Oruche, N.E., Dix, G.R. and Kamo, S.L. 2018. Lithostratigraphy of the upper Turinian–lower Chatfieldian (Upper Ordovician) foreland succession, and a U–Pb ID–TIMS date for the Millbrig volcanic ash bed in the Ottawa Embayment; Canadian Journal of Earth Sciences, v.55, p.1079-1102.

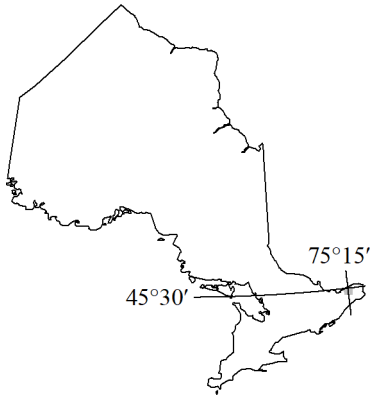
Paton, T.R. and Brett, C.E. 2020. Revised stratigraphy of the middle Simcoe Group (Ordovician, upper Sandbian-Katian) in its type area: An integrated approach; Canadian Journal of Earth Sciences, v.57, p.184-198.

Salad Hersi, O. and Dix, G.R. 1999. Blackriveran (lower Mohawkian, Upper Ordovician) litho-stratigraphy, rhythmicity, and paleogeography: Ottawa Embayment, eastern Ontario, Canada; Canadian Journal of Earth Sciences, v.36, p.2033-2050.

Sanford, B.V. 1993. Stratigraphic and structural framework of Upper Middle Ordovician rocks in the Head Lake–Burleigh Falls area of south-central Ontario; Géographie Physique et Quaternaire, v.47, p.253-268.

Williams, D.A. 1991. Paleozoic geology of the Ottawa–St. Lawrence Lowland, southern Ontario; Ontario Geological Survey, Open File Report 5770, 292p.

23. Project SO-22-002. Paleozoic Geology of Eastern Ontario: Russell–Thurso Area



C. Béland Otis[1]

[1]Earth Resources and Geoscience Mapping Section, Ontario Geological Survey

INTRODUCTION

In 2017, the Earth Resources and Geoscience Mapping Section (ERGMS) of the Ontario Geological Survey (OGS) initiated a multi-year project focussing on the Paleozoic geology of eastern Ontario. The main goals of this project include updating 1:50 000 maps for eastern Ontario underlain by Paleozoic rocks, and to evaluate and refine the stratigraphic nomenclature and structural framework affecting the Phanerozoic stratigraphy (Béland Otis 2017, 2018, 2019).

Eastern Ontario is underlain by Cambrian and Ordovician platformal strata of the Ottawa Embayment of the St. Lawrence Platform. These Paleozoic rocks were last mapped by the OGS in the1980s as a series of 20 geological bedrock maps and a summary report (Williams 1991). During the past 4 decades, this area has undergone major urban development, associated with increased land-use pressure on aggregate resources and groundwater resources. The Paleozoic rocks of eastern Ontario have significant proven and future economic potential—being the source of aggregate, dimension and building stone, calcium carbonate, silica sand, brick and tile, gypsum and other industrial minerals (Tessier et al. 2018, 2019; LeBaron et al. 2020; Mancini et al. 2021). Furthermore, the refinement of the stratigraphy can help improve the regional understanding and predictability of karst landforms (Brunton 2019).

In the last 4 decades, the Cambro-Ordovician stratigraphic units of eastern Ontario have been the focus of academic research. These studies have introduced new stratigraphic units (or re-introduced old terms), revised formational contact definitions and relative ages of some intervals and/or proposed the application in Ontario of stratigraphic terminology used in adjacent jurisdictions instead of the current OGS nomenclature (Williams 1991; Béland Otis 2017, 2018, 2019). In the summer of 2017, the OGS undertook some regional reconnaissance mapping throughout eastern Ontario to gain an overview of the regional geology and to begin to evaluate current and proposed stratigraphic schemes (Béland Otis 2017). Additional field work in the Ottawa and Arnprior–Quyon areas in 2018 and 2019, as well as extensive discussions with ERGMS colleagues, led to a new project to completely revise the Cambro-Ordovician legend of southern Ontario (Béland Otis 2018, 2019; Brunton et al. 2021).

2022 STUDY AREA AND FIELD WORK

Field work in 2022 was dedicated to mapping rock exposures located in the Russell and Thurso areas (Figure 23.1), represented by National Topographic System (NTS) 31 G/6 and 31 G/11 maps, respectively. Additional outcrops and quarries were also mapped in the adjacent areas represented by the Alexandria (31 G/7), Hawkesbury (31 G/10), Winchester (31 G/3) and Cornwall (31 G/2) maps. In Ontario, the

Summary of Field Work and Other Activities, 2022,
Ontario Geological Survey, Open File Report 6390, p.23-1 to 23-8.

© King's Printer for Ontario, 2022

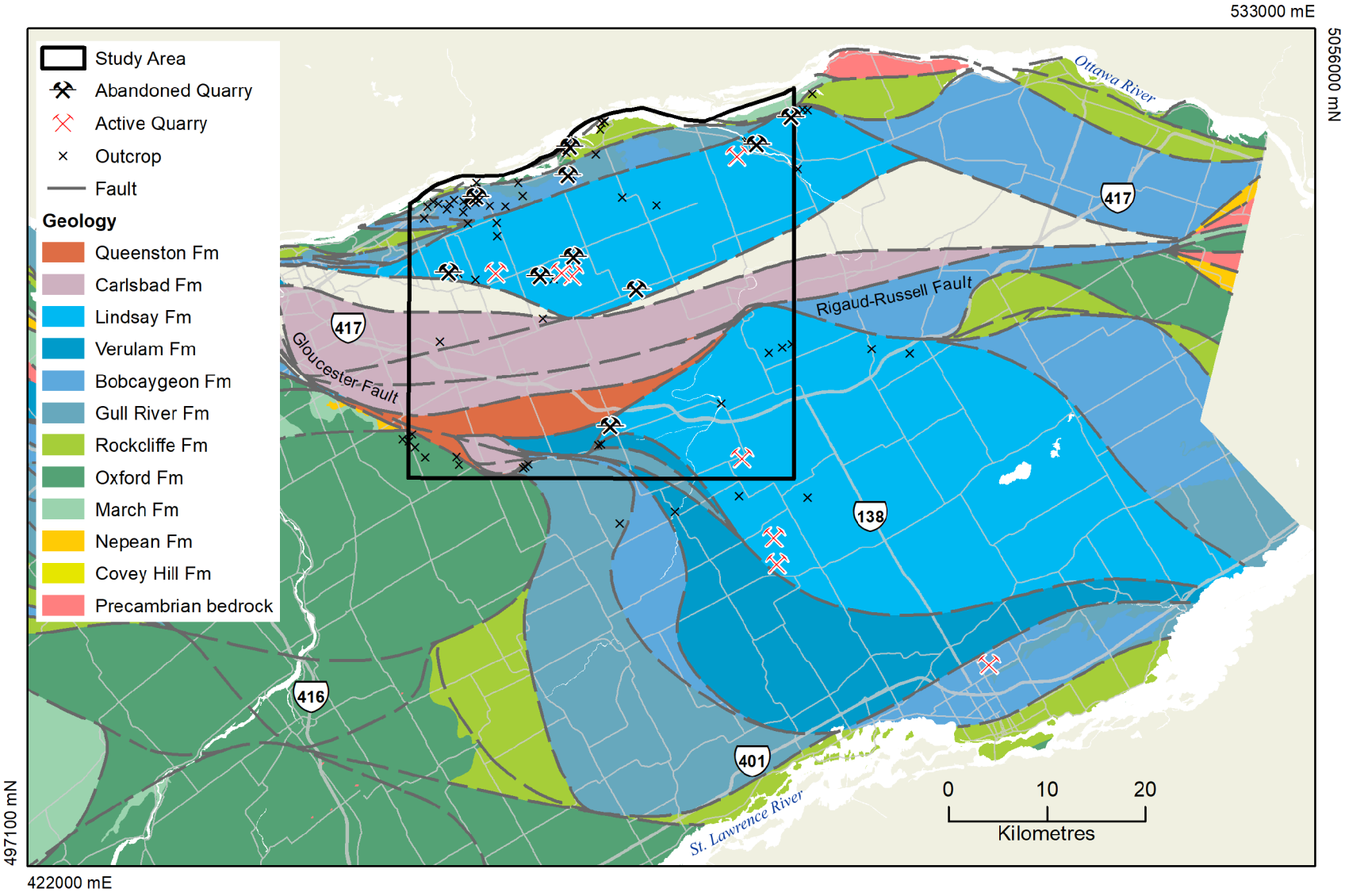


Figure 23.1. Geological bedrock geology of eastern Ontario from the previous mapping (*from* Armstrong and Dodge 2007; *modified from* Williams 1991) showing the locations of the 2022 study area and mapping stations (outcrop and quarries). Abbreviation: Fm = Formation. All Universal Transverse Mercator (UTM) co-ordinates provided using North American Datum 1983 (NAD83) in Zone 18.

Thurso NTS area represents less than 275 km^2 and, therefore, has been combined with the Russell NTS area located to the south. The 2022 field season included the examination of more than 74 outcrops, 8 active and 10 inactive quarries, resulting in 92 field stations.

Additional stations located in the Russell–Thurso map were described in previous years. In 2017, some quarries were visited and, in 2018, some outcrops adjacent to the Ottawa map were mapped. Also, in 2019, cores, drilling cuttings and geophysical logs were examined at the Oil, Gas and Salt Resources in London, which includes wells located in the current study area. These supplementary stations will not be described here, but additional information can be found in previous reports (Béland Otis 2017, 2018, 2019).

The previous OGS mapping of the area took place in 1982 and was accomplished by Williams, Rae and Wolf (1985). Outcrops are mostly located south of the Gloucester fault and along creeks and rivers (*see* Figure 23.1). Active quarries are found predominantly in the middle of the study area, whereas inactive quarries are in the northern portion of the map, closer to the Ottawa River. Not even half of the previous mapping project stations could be described because outcrops were now found covered, either by agriculture and/or urban development.

Paleozoic Stratigraphy of the Russell–Thurso Area

Paleozoic sedimentary rocks subcrop across the entire study area, except for 1 Precambrian outcrop, located near the Ottawa River in the community of Rockland. Within 200 m of this location, the oldest Paleozoic unit of in the Russell–Thurso study area is exposed. The OGS currently refers to this unit as the Nepean Formation of the Potsdam Group, although Lowe et al. (2017) recently proposed to use the name Keeseville Formation of the Potsdam Group, as defined in New York State. It predominantly comprises white quartz arenite with some laminated dolostone beds present at the base of the outcrop. It has been suggested that these should be referred as the Rivière Aux Outardes Member of the Keeseville Formation (Lowe at al. 2017). The top of the member is found at the base of a conglomerate bed, located about a metre above the base of the outcrop. Additionally, Ordovician conodonts were collected from the Rivière Aux Outardes Member (Lowe at al. 2017).

Although the Nepean Formation upper geological contact is not observed on the field, in the GSC #2 Russell core, the unit is overlain by the Beekmantown Group (Williams 1991; Bernstein 1992; Lowe et al. 2017; Béland Otis 2019). According to the OGS nomenclature, the Beekmantown Group is subdivided into the March and Oxford formations, although more recent studies suggest it should be subdivided into the Theresa, Beauharnois and Carillon formations (Williams 1991; Bernstein 1992). In the current study area, only the dark grey, medium- to thin-bedded, pure dolostone beds of the lower Oxford Formation, which is stratigraphically equivalent to the Beauharnois Formation, have been observed. Outcrops have been identified along the Ottawa River and south of the Gloucester fault, in the southwest corner of the map. Other than stromatolitic structures, fossil content is somewhat limited.

The Beekmantown Group is overlain by the green to maroon sandstones and shales of the Rockcliffe Formation, as described from the GSC #2 Russell core (Williams 1991). The unit is mapped in the study area along the Ottawa River where it usually creates an escarpment, resulting from the easy erosion of this shaly unit. The limestone and silty dolostone beds, characteristic of the upper St. Martin Member, were not observed in the study area. One new accessible exposure of the upper part of the unit has been mapped in the new residential development at the northern extent of Cardinal Creek Drive.

A series of limestones, dolostones and shales, known as the Ottawa Group, disconformably overlie the Rockcliffe Formation (Wilson 1946a; Williams 1991). A multitude of stratigraphic nomenclatures has been proposed for this succession and is currently the focus of a stratigraphic revision by the OGS (Brunton et al. 2021). The lowest unit is characterized by medium-bedded tabular greenish grey silty dolostones interbedded with fine crystalline limestones, shales and calcareous sandstones (Photo 23.1A).

Oolitic beds, intraclasts, conchoidal fractures and calcite-filled vugs are all characteristic of the unit. In Ontario, these rocks are mapped as the lower member of the Gull River Formation, whereas in the bordering jurisdictions (e.g., New York State and Quebec), they are recognized as the Pamelia Formation of the Black River Group (Okulitch 1939; Wilson 1946a; Clark 1972; Fisher 1977; Williams 1991). The



Photo 23.1. Selected photographs of 2022 field work. **A**) Medium-bedded tabular beds of greenish dolostone and dark grey limestone of the lower Gull River Formation (Pamelia Formation) at the McLeod quarry in Cornwall. **B**) Bentonite bed found in the limestone of the Lindsay Formation at the Malyon Excavation Ltd. Avonmore quarry. **C**) The view of the Navan Lafarge quarry from the top. **D**) A *Tetradium* colony found in the upper beds of the Gull River Formation (Lowville Formation) in the inactive Stewart quarry in Rockland.

top dolomitic bed represents the top contact of the unit. The upper member of the Gull River Formation, equivalent to the Lowville Formation of the Black River Group of Quebec and New York State, consists of tabular bedded, fine crystalline dark grey limestone and generally weathers bluish grey (Williams 1991; Salad Hersi and Dix 1999). This unit is characterized by birds-eye textures and *Tetradium* colonies are typical for the upper beds (Photo 23.1D). The lower member of the Bobcaygeon Formation of eastern Ontario is characterized by thick to massive beds of finely crystalline dark brownish grey limestone. The presence of chert nodules and/or stylolites is common. Other common names for stratigraphically equivalent units are the Watertown, Coboconk, Chaumont or Leray formations and have generally been assigned to the uppermost Black River Group (Clark 1972; Fisher 1977; Salad Hersi and Dix 1999; Armstrong and Carter 2010; Oruche, Dix and Kamo 2018). In the Russell–Thurso study area, the best locations to examine these Ottawa Group lower strata, equivalent to the Black River Group, are inactive quarries located in Rockland and Cumberland. The MacLeod quarry within the city of Cornwall is also a great exposure of these units for eastern Ontario.

The strata found overlying the lower member of the Bobcaygeon Formation is generally composed of a shaly limestone. In the Embrun area, as well as in the Ottawa and Arnprior–Quyon areas, this middle member of the Bobcaygeon Formation, also called the L'Orignal Formation, usually only measures a few metres thick (Williams 1991; Oruche, Dix and Kamo 2018). However, in the Rockland Stewart quarry, only a 2 to 3 cm thick shaly bed is found over the lower member of the Bobcaygeon Formation (Oruche, Dix and Kamo 2018). Furthermore, at this location, the Bobcaygeon Formation upper member is characterized by thick rhythmic beds of grainstone to mudstone. These rocks have been mapped as the Rockland Formation of the Trenton Group by various authors (Raymond 1914; Barnes 1967; Oruche, Dix and Kamo 2018). In most other localities, the upper member of the Bobcaygeon Formation is represented by thick bedded brownish grey calcarenites, usually cross-bedded, alternatively named the Hull Formation of the Trenton Group (Uyeno 1974; Oruche, Dix and Kamo 2018). The relationship between the Rockland and Hull formations remains unclear.

The upper contact of the Bobcaygeon Formation with the Verulam Formation is rarely observed in outcrop. In 2022, the Verulam Formation was mapped only along riverbeds and in lower benches of quarries for which the Lindsay Formation is at surface. It is composed of fossiliferous, lenticular and discontinuous, irregular thin- to medium-bedded dark grey wackestone to grainstone interbedded with calcareous black shale (Williams 1991). Major components of the limestone beds include intraclasts, echinoderms, bryozoans, brachiopods and trilobites.

The upper contact of the Verulam Formation with the Lindsay Formation was placed at the uppermost shale bed greater than 5 cm thick, as discussed by Williams (1991). Most of the quarries in the middle of the Russell–Thurso study area extract the Lindsay Formation (Photo 23.1C). It is composed of thin to thick nodular bedded light to dark grey wackestone to packstone with some 2 to 3 cm thick calcareous shale interbeds. During field work, a bentonite bed was identified and sampled in the Malyon Excavation Ltd. Avonmore quarry (Photo 23.1B). The upper Eastview Member, composed of dark brownish micrite and the upper geological contact of the Lindsay Formation were not observed this summer.

The youngest Paleozoic sediments found in the study area are a succession of Ordovician shales, composed of the Billings, Carlsbad and Queenston formations. The Billings Formation largely comprises dark grey to black non-calcareous shale, but, near the top, there is a general increase of siltstone and limestone beds. The upper contact with the Carlsbad Formation is defined as the base of the lowest limestone bed greater than 2 cm thick (Williams 1991). The Carlsbad Formation is composed of interbedded shale, fossiliferous siltstone and limestone. The unit becomes quite calcareous near the top and its upper contact is the lower limit of the Queenston Formation red shales. Because of the low resistance of those shales, outcrop exposure is quite limited. Within the study area, only the Billings Formation was identified at 1 riverbank outcrop. However, the distinctive red Queenston Formation is also exposed in the soil overlying the unit.

Structural Geology of the Russell–Thurso Area

The study area is structurally complex. Indeed, 2 major faults, the Gloucester and the Rigaud–Russell faults intersect in the southwest corner of the study area (*see* Figure 23.1; Wilson 1940, 1946b; Globensky 1982; Williams 1991; Sanford and Arnott 2010). Additionally, a series of northwest-oriented faults is present along the Ottawa River (Wilson 1940, 1946b; Sanford and Arnott 2010). Strongly dipping strata is usually indicative of nearby faults (Williams 1991; Béland Otis 2018). However, in the current study area, only a large fold is observed along the Castor River in Russell. Also, the precise position and orientation of faults are difficult to map because of limited outcrop exposure.

FUTURE WORK

The study area has only limited outcrop exposure because of easily weathered shale units, but primarily because of other land use (e.g., agriculture, urban areas). Also, multiple outcrops consisted of pavements, limiting stratigraphic information. In the short term, a few steps are being undertaken to improve our geological knowledge of the area: 1) field notes of Williams, Rae and Wolf (1985) are currently in the process of being digitized and should include additional outcrops from Wilson's (1940) map; 2) thorough review of water and geotechnical wells; 4) integration of data from deep stratigraphic and oil and gas wells, which are all located in the southwest corner of the study area.

Additional work will also include the preparation, examination and description of thin sections from samples collected during the summer 2022. Furthermore, analyses of geochemical analyses will be reviewed and compared to see variability of each unit regionally when all results are made available. The bentonite collected in the Lindsay Formation will also be submitted for geochronological analysis.

A concurrent OGS project involving the stratigraphic revision of the Paleozoic legend of all of southern Ontario was initiated in 2021 (Brunton et al. 2021). The current project field work and data collected will support this parallel project.

ACKNOWLEDGMENTS

The author wishes to acknowledge the assistance of Nathan Mask during the field season and to thank Frank Brunton, Katie Hahn and Riley Mulligan (ERGMS) for their insight in the field. Also, the author would like to thank quarry owners and operators (including Cornwall Gravel Co. Ltd., Lafarge Canada, Malyon Excavation Ltd., Tomlinson Group, Brigil Construction), as well as private owners, for granting access and allowing sample collection on their properties. The author would like to thank the Algonquins of Pikwakanagan First Nation for allowing the Ontario Geological Survey to map their traditional land use area. The author is also thankful to all the ERGMS staff, particularly Kei Yeung (GIS technical help) and Julien Bonin (drafting figures). Finally, the Geoscience Laboratories and the Publication Services Unit staff are acknowledged for their help throughout this project.

REFERENCES

Armstrong, D.K. and Carter, T.R. 2010. The subsurface Paleozoic stratigraphy of southern Ontario; Ontario Geological Survey, Special Volume 7, 301p.

Armstrong, D.K. and Dodge, J.E.P. 2007. Paleozoic geology of southern Ontario; Ontario Geological Survey, Miscellaneous Release—Data 219.

Barnes, C.R. 1967. Stratigraphy and sedimentary environments of some Wilderness (Ordovician) limestones, Ottawa Valley, Ontario; Canadian Journal of Earth Sciences, v.4, p.209-244.

Béland Otis, C. 2017. Paleozoic geology of eastern Ontario; *in* Summary of Field Work and Other Activities, 2017, Ontario Geological Survey, Open File Report 6333, p.22-1 to 22-11.

——— 2018. Paleozoic geology of eastern Ontario: Ottawa area; *in* Summary of Field Work and Other Activities, 2018, Ontario Geological Survey, Open File Report 6350, p.22-1 to 22-10.

——— 2019. Paleozoic geology of eastern Ontario: Arnprior–Quyon area; *in* Summary of Field Work and Other Activities, 2019, Ontario Geological Survey, Open File Report 6360, p.20-1 to 20-10.

Bernstein, L. 1992. A revised lithostratigraphy of the Lower–Middle Ordovician Beekmantown Group, St. Lawrence Lowlands, Quebec and Ontario; Canadian Journal of Earth Sciences, v.29, p.2677-2694.

Brunton, F.R. 2019. Karst map of southern Ontario: An update; *in* Summary of Field Work and Other Activities, 2019, Ontario Geological Survey, Open File Report 6360, p.21-1 to 21-9.

Brunton, F.R., Béland Otis, C., Hahn, K.E. and Yeung K.H. 2021. Progress on the development of a new stratigraphic framework for the Paleozoic geology of southern Ontario; *in* Summary of Field Work and Other Activities, 2021, Ontario Geological Survey, Open File Report 6380, p.16-1 to 16-9.

Clark, T.H. 1972. Montreal area; Ministère des Richesses Naturelles du Québec, Geological Report 152, 244p.

Fisher, D.W. 1977. Correlation of the Hadrynian, Cambrian and Ordovician Rocks in New York State; New York State Museum and Science Service, Map and Chart Series 25, 75p.

Globensky, Y. 1982. Région de Vaudreuil; Ministère de l'Énergie et des Ressources du Québec, Rapport Géologique 199, 59p.

LeBaron, P.S., Sabiri, N., Laidlaw, D.A., Hinz, S.L.K. and Fortner, L. 2020. Report of Activities 2019, Resident Geologist Program, Southern Ontario Regional Resident Geologist Report: Southeastern and Southwestern Ontario Districts and Petroleum Operations; Ontario Geological Survey, Open File Report 6368, 72p.

Lowe, D.G., Arnott, R.W.C., Nowlan, G.S. and McCracken, A.D. 2017. Lithostratigraphic and allostratigraphic framework of the Cambrian–Ordovician Potsdam Group and correlations across Early Paleozoic southern Laurentia; Canadian Journal of Earth Sciences, v.54, p.550-585.

Mancini, L.A., Meek, R.D., Sabiri, N., LeBaron, P.S., Rodriguez Miguel, L.M., Hinz, S.L.K., Dorland, G., Patterson, C. and Fortner, L. 2021. Report of Activities 2020, Resident Geologist Program, Southern Ontario Regional Resident Geologist Report: Southeastern Ontario and Southwestern Ontario Districts and Petroleum Operations; Ontario Geological Survey, Open File Report 6376, 67p.

Okulitch, V.J. 1939. The Ordovician section at Coboconk, Ontario; Royal Canadian Institute, Transactions, v.33, p.319-339.

Oruche, N.E., Dix, G.R. and Kamo, S.L. 2018. Lithostratigraphy of the upper Turinian–lower Chatfieldian (Upper Ordovician) foreland succession, and a U–Pb ID–TIMS date for the Millbrig volcanic ash bed in the Ottawa Embayment; Canadian Journal of Earth Sciences, v.55, p.1079-1102.

Raymond, P.E. 1914. The Trenton Group in Ontario and Quebec; *in* Summary Report for the Year 1912, Geological Survey of Canada, p.342-350.

Salad Hersi, O. and Dix, G.R. 1999. Blackriveran (lower Mohawkian, Upper Ordovician) litho-stratigraphy, rhythmicity, and paleogeography: Ottawa Embayment, eastern Ontario, Canada; Canadian Journal of Earth Sciences, v.36, p.2033-2050.

Sanford, B.V. and Arnott, R.W.C. 2010. Stratigraphic and structural framework of the Potsdam Group in eastern Ontario, western Quebec and northern New York State; Geological Survey of Canada, Bulletin 597, 83p.

Tessier, A.C., LeBaron, P.S., Charbonneau, S.J., Laidlaw, D.A., Wilson, A.C. and Fortner, L. 2018. Report of Activities 2017, Resident Geologist Program, Southern Ontario Regional Resident Geologist Report: Southeastern Ontario and Southwestern Ontario Districts and Petroleum Operations; Ontario Geological Survey, Open File Report 6341, 93p.

Tessier, A.C., LeBaron, P.S., Smith, A.C., Laidlaw, D.A., Bousquet, P. and Fortner, L. 2019. Report of Activities 2018, Resident Geologist Program, Southern Ontario Regional Resident Geologist Report: Southeastern Ontario and Southwestern Ontario Districts and Petroleum Operations; Ontario Geological Survey, Open File Report 6356, 94p.

Uyeno, T.T. 1974. Conodonts of the Hull Formation, Ottawa Group (Middle Ordovician), of the Ottawa–Hull area, Ontario and Quebec; Geological Survey of Canada, Bulletin 248, 31p.

Williams, D.A. 1991. Paleozoic geology of the Ottawa–St. Lawrence Lowland, southern Ontario; Ontario Geological Survey, Open File Report 5770, 292p.

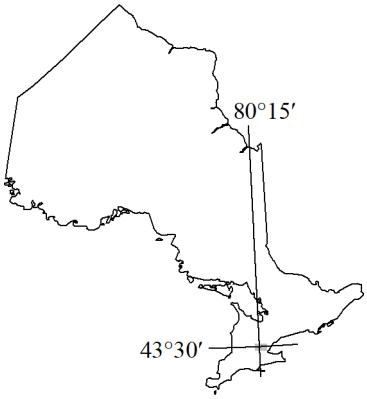
Williams, D.A., Rae, A.M. and Wolf, R.R. 1985. Paleozoic geology of the Russell–Thurso area, southern Ontario; Ontario Geological Survey, Preliminary Map P.2717, scale 1:50 000.

Wilson, A.E. 1940. Casselman; Geological Survey of Canada, Map 587A, scale 1:126 720.

——— 1946a. Geology of the Ottawa–St. Lawrence Lowland, Ontario and Quebec; Geological Survey of Canada, Memoir 241, 66p.

——— 1946b. Ottawa–Cornwall; Geological Survey of Canada, Map 852A, scale 1:253 440.

24. Project SO-22-005. From Mighty Moraines to Dramatic Drumlins: Introducing the Guelph Three-Dimensional Sediment Mapping Project



A.K. Burt[1] and G.W. Hagedorn[1]

[1]Earth Resources and Geoscience Mapping Section, Ontario Geological Survey

INTRODUCTION

The Ontario Geological Survey (OGS) has been actively engaged in three-dimensional (3-D) mapping of Quaternary sediments in southern Ontario since 2002. There are many drivers for working in southern Ontario. Quaternary sediments host regionally significant aquifers relied upon for drinking water, industry, agriculture and recreation. Groundwater is also important for maintaining ecosystems such as cold-water streams and wetlands. However, population growth, often leap-frogging beyond the Greenbelt (Figure 24.1A), and a long history of agriculture and industry causes many threats to water safety. Accurate surficial and subsurface sediment information is required to develop sound land-use planning decisions for our built environment, in conjunction with supporting both agricultural and aggregate industries. Maintaining the wetlands that provide natural flood protection, as well as defining and protecting groundwater recharge zones, is also vital for a healthy and prosperous Ontario.

Previous 3-D sediment mapping projects have focussed on regions slated for urban growth, where Quaternary sediments host prolific aquifers and/or exhibit strong controls on surface water-groundwater systems. Past areas include the completed Barrie–Oro Moraine (Burt and Dodge 2011) and South Simcoe (Bajc, Mulligan and Dodge 2019) models, as well as ongoing work in the central part of the County of Simcoe (Mulligan 2020) below the Niagara Escarpment. Above the Niagara Escarpment, the completed Waterloo Region (Bajc and Shirota 2007), Brantford–Woodstock (Bajc and Dodge 2011) and Orangeville–Fergus (Burt and Dodge 2016), models are centred over the Late Wisconsin interlobate zone, which extends southwest from the city of Orangeville. The ongoing Niagara Peninsula model (Burt 2017, 2020) extends from the interlobate zone eastward to the Niagara River, leaving a gap centred on the City of Guelph. This summer, the OGS initiated a new 3-D sediment mapping project in the Guelph area, which will provide continuous coverage above the Niagara Escarpment.

GUELPH THREE-DIMENSIONAL SEDIMENT MAPPING PROJECT AREA

The Guelph 3-D sediment mapping project encompasses approximately 1400 km^2 extending from the Niagara Escarpment westward toward the Grand River and Waterloo moraine. The study area overlaps the Orangeville–Fergus 3-D area in the north and the Brantford–Woodstock and Niagara Peninsula 3-D areas in the south by between 2 and 3.5 km to minimize edge matching issues with older models. The irregularly shaped Waterloo Region 3-D model was created using an older version of Datamine Studio® software, thus, a larger overlap of between 5 and 25 km is planned. This will allow the wealth of subsurface information and hydrogeological model results accumulated in the 15 years since the Waterloo Region 3-D project was released to be incorporated into a new 3-D sediment model.

Summary of Field Work and Other Activities, 2022,
Ontario Geological Survey, Open File Report 6390, p.24-1 to 24-10.

© King's Printer for Ontario, 2022

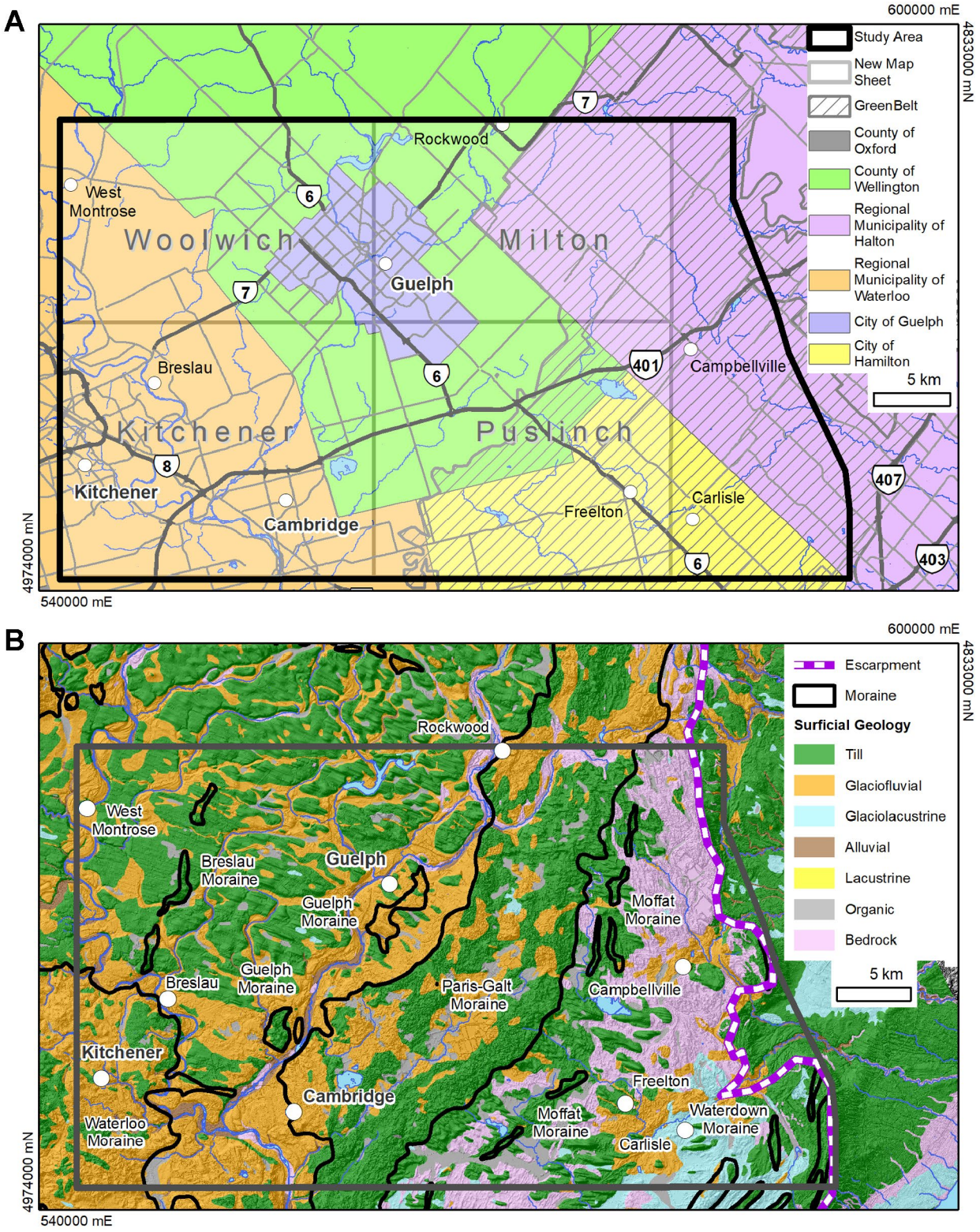


Figure 24.1. A) Location map of the Guelph study area showing the locations of the 4 new surficial geology maps planned as part of this project. The Milton and Puslinch area maps are highest priority. **B)** Generalized surficial geology map of the Guelph study area (Ontario Geological Survey 2010) overlain on a lidar-derived digital terrain model hillshade (Ministry of Natural Resources and Forestry 2022) showing locations of moraines. Data are projected using North American Datum 1983 (NAD83) Universal Transverse Mercator (UTM) in Zone 17N.

Included within the study area (*see* Figure 24.1A) are portions of Wellington County (Township of Centre Wellington, Township of Guelph–Eramosa and Township of Puslinch), the Regional Municipality of Waterloo (Township of Woolwich, City of Waterloo, City of Kitchener, City of Cambridge and Township of North Dumfries), the Regional Municipality of Halton (Town of Halton Hills, Town of Milton and City of Burlington), the City of Guelph and the City of Hamilton (*see* Figure 24.1A). These areas are represented by 1:50 000 scale National Topographic System (NTS) maps 40 P/8 (Cambridge), 40 P/9 (Guelph), 30 M/5 (Burlington) and 30 M/12 (Brampton). Major urban areas include the cities of Guelph, Kitchener and Cambridge. The communities of Rockwood, West Montrose, Breslau, Freelton, Carlisle and Campbellville, as well as numerous smaller villages and hamlets are also located within the study area. A comprehensive road network, ranging from provincial highways to county and local township roads, provides access throughout the area.

REGIONAL SETTING

Bedrock Geology

The Guelph 3-D study area is underlain by southwestward-dipping Ordovician and Silurian bedrock formations (Armstrong and Carter 2010; Brunton and Brintnell 2011). East of the Niagara Escarpment, the surface of the Upper Ordovician Queenston Formation (red and green shale) slopes toward Lake Ontario. The Niagara Escarpment is marked by intermittent benches formed by resistant lithologies within the Lower Silurian Clinton–Medina groups shale, sandstone, dolostone and limestone. The Lockport Group forms the principal cuesta and, in ascending order, comprises the Gasport Formation dolostone; Goat Island Formation argillaceous, locally cherty, dolostone; Eramosa Formation bituminous dolostone; and Guelph Formation vuggy dolostone. The Goat Island and Guelph formations crop out and subcrop across much of the eastern and central portions of the study area. The western portion of the study area is characterized by subcropping Upper Silurian Salina Group calcareous shale, dolostone, gypsum and anhydrite.

A series of prominent re-entrants along the escarpment marks the locations of partially filled to completely buried bedrock valleys (Burt 2018). Tributaries of the Elora, Rockwood and Black Creek buried-bedrock valley systems, modelled as part of the Orangeville–Fergus 3-D project and the subject of ongoing research at the University of Waterloo and the University of Guelph, dominate the northern and central portion of the Guelph study area (Conway-White et al. 2022; Ontario Geological Survey 2013; Steelman et al. 2018). Buried-bedrock valleys associated with the modern 16 Mile Creek and Bronte Creek are located in the southern and eastern portions of the area.

Quaternary History and Surficial Geology

Multiple cycles of glacial advance and retreat across Ontario have resulted in a complex record of glacial and nonglacial deposits. Existing 3-D sediment models (Bajc and Shirota 2007; Bajc and Dodge 2011; Burt and Dodge 2016) and the regional-scale drift thickness map (Gao et al. 2006) suggest that, in the Guelph area, the oldest and thickest sediment successions are in the west, whereas younger and thinner sediment successions are encountered near the Niagara Escarpment in the east. Sediments predating the last glacial maximum do not crop out within the Guelph 3-D study area, but are documented in the literature (e.g., Greenhouse and Karrow 1994) and have been modelled as a series of 4 regional-scale aquifers and aquitards in adjacent 3-D areas (Burt and Bajc 2020). During the last glacial maximum, the Erie–Ontario and Huron–Georgian Bay lobes, advanced into proglacial lakes followed by a regional southerly ice advance that deposited Catfish Creek Till, an important marker bed across southwestern Ontario. During deglaciation, the ice sheet thinned and evolved into semi-independent lobes, with

meltwater and sediments deposited into an interlobate zone extending from Orangeville to southwest of London. Interbedded diamicton and coarse- and fine-grained stratified sediments, comprising the Maryhill drift, and the large sandy fans and gravelly conduits, comprising the Dorchester, Waterloo and Orangeville moraines, were deposited in this zone (Bajc and Shirota 2007; Burt and Dodge 2016).

During the late glacial Port Bruce Phase, the Erie–Ontario lobe advanced across the Guelph area depositing Port Stanley Till, partially burying the eastern flanks of the Waterloo moraine (Bajc and Shirota 2007). Port Stanley Till forms the uppermost till in the northwestern portion of the Guelph study area and recent lidar imagery reveals that the surface is characterized by both mega-scale glacial lineations and drumlins with a strong northwest orientation. As the ice retreated, sand and gravel glaciofluvial outwash was deposited within an extensive network of meltwater channels incised into the till surface and underlying deposits (Figure 24.1B).

The Paris–Galt moraines, deposited by a readvance of the Ontario lobe, occur as a wide southwest-trending composite feature consisting of ridged and hummocky diamicton, coarse-textured ice-contact stratified drift and relatively flat-lying gravelly glaciofluvial outwash as shown on Figure 24.1B (Karrow 1963a, 1963b, 1968a, 1968b; Ontario Geological Survey 2010). Wetlands and organic deposits are found in depressions within the hummocky portions of the moraine and are locally extensive within associate outwash plains and channels. East of the Paris–Galt moraines, the sediment cover thins and pinches out toward the Niagara Escarpment. Much of this area is mapped as bedrock or a bedrock–drift complex overlain by the discontinuous Moffat moraine, eskers and stratified ice-contact sediments deposited as retreat continued (*see* Figure 24.1B; Karrow 1987a, 1987b). Wetlands and organic deposits, including the well-known Beverly and Fletcher Creek Southern Forest Swamps (designated as Areas of Natural and Scientific Interest (ANSIs) and Provincially Significant Wetlands; Hamilton Region Conservation Authority 2020) occupy extensive portions of this area, contributing to the appearance of a typically low-relief landscape. The most distinctive features in this portion of the study area are the variably west- to northwest-oriented drumlins, composed of stony Wentworth Till, which rise over 30 m above the surrounding landscape.

The late glacial (Port Huron Phase) advance of the Ontario lobe deposited a series of low moraines composed of clayey Halton Till and sandy fans, collectively termed the Waterdown moraines, and outwash along the top of the Niagara Escarpment in the far southeast of the study area (*see* Figure 24.1B). The ice was fronted by, and advanced into, glacial Lake Whittlesey and the moraines are draped by glaciolacustrine silt and sand. Shorelines attributed to glacial Lake Whittlesey are clearly visible along the flanks of some drumlins west of the moraines.

Surface Drainage

Surface drainage is controlled by a combination of the bedrock topographic surface, primarily the Niagara Escarpment, and the topography of the overlying Quaternary sediment cover. There are 3 major drainage basins within the area, which form the boundaries of the Grand River Conservation Authority in the central and western portion of the area, the Halton Conservation Authority in the northeast and the Hamilton Conservation Authority in the southeast.

PROJECT PLANS

Currently, the surficial geology of the study area is represented on 4 maps: Guelph and Brampton in the north and Cambridge and Hamilton in the south. Early mapping was at a scale of 1:63 360 and later updated to 1:50 000 (Karrow 1963b, 1963c, 1968b, 1987b, 1987c). Lidar-derived bare-earth digital terrain models (DTMs) with a 50 cm spatial resolution and non-vegetated vertical accuracy of 5 to 10 cm are

now available (Ministry of Natural Resources and Forestry 2022). A desktop comparison of the existing surficial mapping and new lidar coverage indicates that a revision of the mapped geological contacts is warranted. For the southern half of the Guelph area and the northern half of the Cambridge area (represented by NTS maps 40 P/9 and 40 P/8, respectively), 4 new 1:20 000 scale surficial geology maps are planned, tentatively referred to as the Woolwich, Milton, Kitchener and Puslinch area maps (*see* Figure 24.1A). Of these, the eastern Milton and Puslinch maps are the highest priority because they include the Paris, Galt and Moffat moraines, as well as the thin drift areas along the Niagara Escarpment.

A ground gravity geophysical survey will be conducted at targets within the study area. The objective of this survey is to investigate known or predicted buried-bedrock valleys west of the Niagara Escarpment, as well as search for outlets of major buried valley systems below the escarpment. The new survey lines will tie in with existing surveys for the Orangeville–Fergus (Ontario Geological Survey 2013), the Niagara Peninsula (Ontario Geological Survey 2014) and the Dundas Valley (Marich et al. 2011) areas. The survey will aid in the selection of drill targets and inform the 3-D model in areas not drilled. It is anticipated that continuous coring of the overburden and upper 3 m of bedrock will take place during the 2023 field season and monitoring wells will be installed by conservation authorities and municipalities at sites of greatest hydrogeologic interest.

A standardized database will be assembled from existing subsurface information. As with previous OGS 3-D modelling projects, Datamine Studio® software, a software package developed for the mining industry and adapted for overburden mapping for groundwater modelling applications, will be used for modelling and the preliminary generation of products (*see* Bajc and Newton (2005) and Bajc and Shirota (2007) for more information on the scripts; *see also* Burt and Dodge (2016) for more information on database standardization). The database, model and a detailed report is planned to be released as part of the OGS Groundwater Resources Study series.

FIELD ACTIVITIES

Field operations were conducted from June to August 2022 and targeted the Puslinch map area and the surrounding thin drift portion of the study area. A total of 675 sites were investigated, including surface observations, shallow test pits, excavations, inactive aggregate operations, road, ditch and river cuts, soil probe and hand-auger sites up to 5.75 m deep (Photo 24.1A). Probe and hand-auger sites were extended to the depth at which work could not proceed, rather than terminating at the 1 m standard depth for surficial mapping projects, as this is a cost-effective alternative to geotechnical drilling for obtaining the stratigraphic information required for 3-D modelling in thin drift areas.

Paris–Galt Moraines

The landform assemblages forming the Paris–Galt moraines have been well studied around the City of Guelph (e.g., Arnaud et al. 2018) and the moraine has been modelled in adjacent 3-D areas (Burt and Bajc 2020) This project will extend both regional-scale subsurface and detailed surficial landform mapping to provide information for future land use planning decisions. In the Guelph area, the Paris–Galt moraines comprise 2 distinct broad zones of hummocky topography with closed drainage depressions separated by low-lying glaciofluvial outwash and large ice-supported fans along the western, down-ice edge of the moraine system (Figure 24.2C). Additional observations of the moraine from this field season include distinct south-trending ridges cut by meltwater channels, eskers terminating in ridges or small fans, and the inverted topography suggestive of ice-walled lakes.

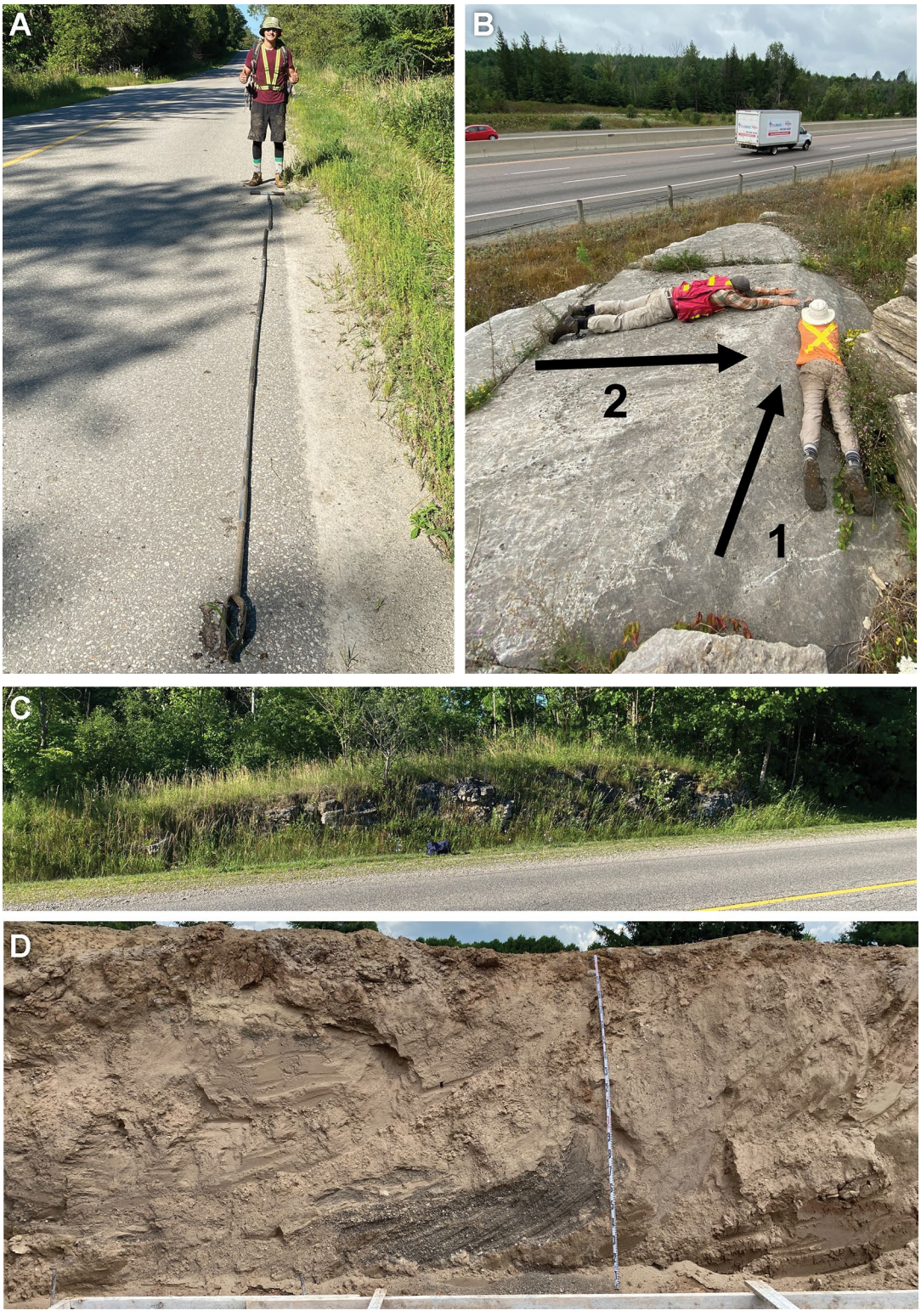


Photo 24.1. A) Adam Kelly with set-up for hand augering a 5.75 m deep hole. **B)** Bedrock ridge (one of the famed Highway 401 "rock drumlins") with multiple ice-flow directions. Abigail Burt (arrow 1) is showing older regional southwest ice-flow direction and Grant Hagedorn (arrow 2) is showing the younger Ontario lobe northwest ice-flow direction. **C)** Example of a cross-sectional profile through bedrock ridge along a road cut. Section is approximately 1 m high. **D)** Example of ice-contact stratified deposits in a moraine ridge. The ice margin would have been to the right, with paleo-ice flow toward the left. Section is approximately 2 m high.

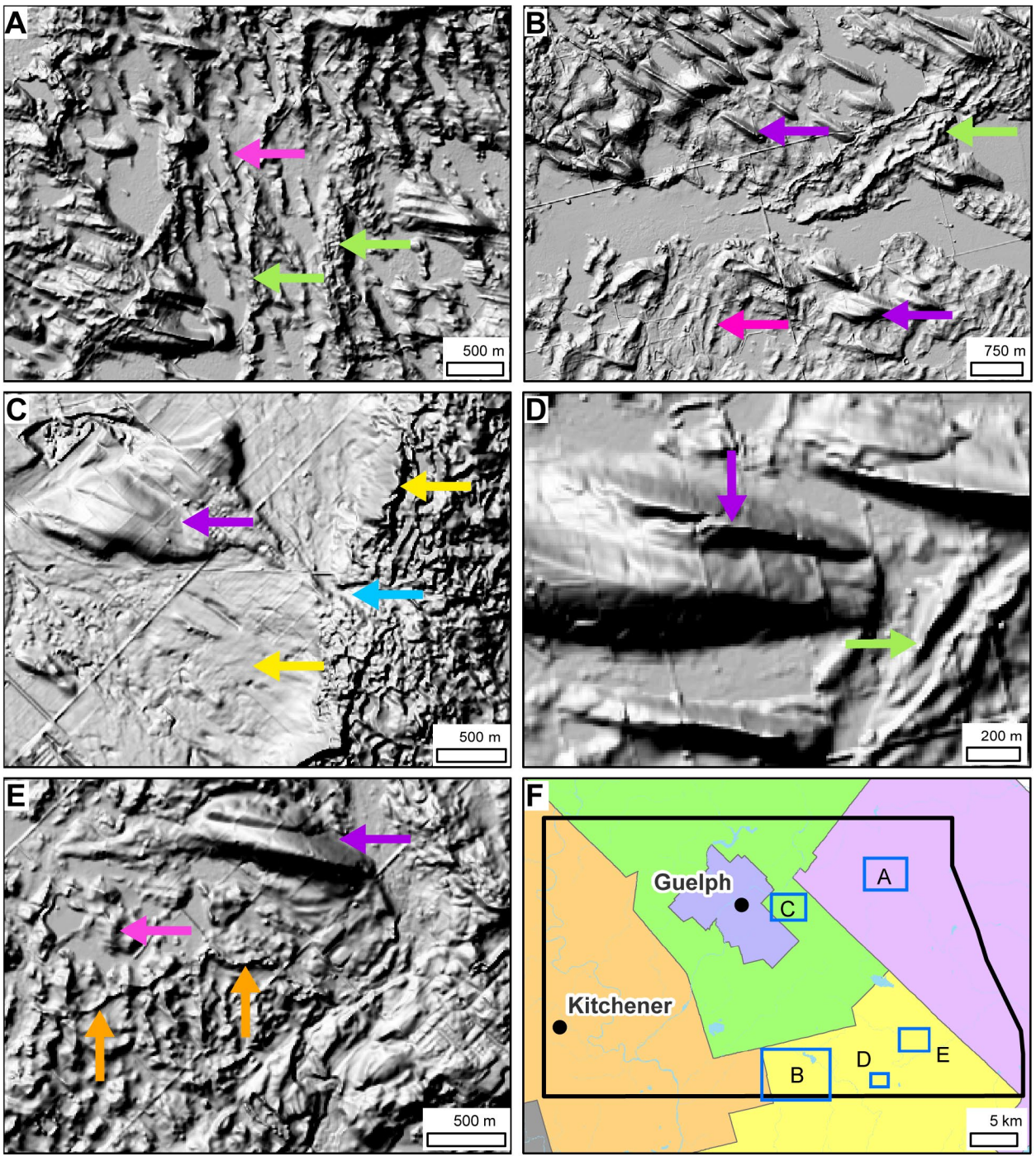


Figure 24.2. Examples of landforms identified using a lidar-derived digital terrain model hillshade (Ministry of Natural Resources and Forestry 2022) from the Guelph area. Locations of panels **A** to **E** are shown on panel **F**. Landforms mentioned in the text are highlighted by arrows. **A)** Bedrock ridge (pink arrow) and moraine ridges (green arrows). **B)** Drumlins (purple arrows), bedrock ridge (pink arrow) and moraine ridge (green arrow). **C)** Steeply sloping ice-contact fan showing position of ice-front and gently sloping distal portion of ice-contact fan (yellow arrows), meltwater channel that cuts through the moraine (blue arrow) and erosional remnant of older drumlinized till (purple arrow). **D)** Overprinted drumlin (purple arrow) and moraine ridges (green arrow). **E)** Esker (orange arrows) and drumlin (purple arrow) overlying bedrock ridges (pink arrow). Data are projected using North American Datum 1983 (NAD83) Universal Transverse Mercator (UTM) in Zone 17N.

Low-Relief Ridges

The new lidar-based DTM reveals a series of low-relief ridges that are difficult to characterize on lower resolution digital elevation models (DEMs). They are found in the eastern to southeastern portion of the study area where thin sediments overlie Lockport Group dolostones of the Niagara Escarpment. Older surficial mapping shows large areas of bedrock and bedrock with a thin veneer of sediment, as well as several discontinuous segments of moraine ridges, the Moffat moraine and glaciofluvial deposits (*see* Figure 24.1B). The ridges are typically spaced between 100 and 300 m apart and range from a north-south to northeast-southwest orientation (Figures 24.2A and 24.2B). Their location, orientation and general characteristics suggest 2 possible origins for the ridges: primary bedrock features or moraines. Developing a set of criteria to facilitate remote identification of the 2 types of ridges was a primary focus of field investigations (Photos 24.1C and 24.1D). Careful ground truthing revealed that bedrock ridges were less sinuous, had a more consistent axis orientation and spacing and, in some areas, had clear down-ice streamlining (crag and tails). The moraine ridges could be distinguished from the bedrock ridges by their more sinuous crests, slightly to strongly discordant orientation to the bedrock crests and lack of down-ice streamlining. It is noteworthy that there appear to be many more moraine ridges than previously identified, including several distinct ridges comprising the Moffat moraine and numerous moraine ridges that are not associated with a previously named moraine system (*see* Figure 24.2B). The identification of the minor moraine ridges along with other landforms now observable, including meltwater channels, eskers, fans, and streamlined landforms, allows for the development of a more complete understanding of the glacial history of this region of Ontario (Figures 24.2D and 24.2E).

One particularly interesting area that the new lidar data set has provided clarity on are the famed “rock drumlins” visible from Highway 401. The lidar data set clearly shows that these “drumlins” are, in fact, examples of the bedrock ridges characteristic of this area. The surface of these ridges reveals evidence of an older southwest ice-flow direction and younger northwest ice-flow direction with grooves, striations and chattermarks ranging from 295° to 310° (Photo 24.1B).

Drumlins

Surface tills throughout the Guelph study area are typically drumlinized (*see* Figures 24.1B and 24.2B to 24.2E). A close inspection of the lidar data suggests that, west of the Paris–Galt moraines, there is a westward continuum of bedforms, including drumlins, channeled drumlins and mega-scale glacial lineations, with a strong northwest orientation. In the eastern portion of the study area, the strong northwest orientation observed west of the Paris–Galt moraines gives way to reworked landforms showing west to northwest ice-flow directions (*see* Figures 24.2B to 24.2E). The bedforms show a marked range in size from less than 300 m in length and 10 m in height to greater than 1.5 km in length and 30 m in height. Some are composite forms and, in places, there are 2 orientations along a single feature suggesting overprinting. Bedrock ridges are evident beneath the smallest drumlins; and perpendicular low-relief ridges, likely moraine ridges, can be seen on the flanks of some larger bedforms.

ACKNOWLEDGMENTS

The authors would like to thank Mississaugas of the Credit First Nation and Six Nations of the Grand River for allowing the Ontario Geological Survey to map their traditional land use area. The chiefs and councils are thanked for their interest and support of this project.

The success of any project depends on having a great team. The project was originally conceived and developed in collaboration with Sonja Strynatka (Grand River Conservation Authority). Sonja has kindly agreed to continue her role as part of a project advisory team. Kei Yeung and Julie Chartrand prepared

our data sets and kept our technology running smoothly throughout the field season. University of Guelph student Adam Kelly's hard work, local knowledge, desire to learn and thought-provoking conversations made this summer a pleasure. Physical geography, geomatics and conservation are a powerful combination. Thanks Adam! Back in the office, Julien Bonin drafted figures and Riley Mulligan reviewed this summary report.

REFERENCES

Armstrong, D.K. and Carter, T.R. 2010. The subsurface Paleozoic stratigraphy of southern Ontario; Ontario Geological Survey, Special Volume 7, 301p.

Arnaud, E., McGill, M., Trapp, A. and Smith, J.E. 2018. Subsurface heterogeneity in the geological and hydraulic properties of the hummocky Paris Moraine, Guelph, Ontario; Canadian Journal of Earth Sciences, v.55, p.768-785. doi.org/10.1139/cjes-2016-0161

Bajc, A.F. and Dodge, J.E.P. 2011. Three-dimensional mapping of surficial deposits in the Brantford–Woodstock area, southwestern Ontario; Ontario Geological Survey, Groundwater Resources Study 10, 86p.

Bajc, A.F., Mulligan, R.P.M. and Dodge, J.E.P. 2019. Three-dimensional mapping of surficial deposits in the southern part of the County of Simcoe, south-central Ontario; Ontario Geological Survey, Groundwater Resources Study 18.

Bajc, A.F. and Newton, M.J. 2005. Three-dimensional modelling of Quaternary deposits in Waterloo Region, Ontario: A case study using Datamine Studio® software; *in* Summary of Field Work and Other Activities, 2005, Ontario Geological Survey, Open File Report 6172, p.25-1 to 25-8.

Bajc, A.F. and Shirota, J. 2007. Three-dimensional mapping of surficial deposits in the Regional Municipality of Waterloo, southwestern Ontario; report *in* Ontario Geological Survey, Groundwater Resources Study 3, 42p.

Brunton, F.R. and Brintnell, C. 2011. Final update of Early Silurian stratigraphy of the Niagara Escarpment and correlation with subsurface units across southwestern Ontario and the Great Lakes Basin; *in* Summary of Field Work and Other Activities, 2011, Ontario Geological Survey, Open File Report 6270, p.30-1 to 30-11.

Burt, A.K. 2017. Graphic logs with analytical and geochronological data from hand auger, probe and section sites in the Niagara Peninsula; Ontario Geological Survey, Miscellaneous Release—Data 353.

——— 2018. Three-dimensional hydrostratigraphy of the Orangeville Moraine area, southwestern Ontario, Canada; Canadian Journal of Earth Sciences, v.55, p.802-828. doi.org/10.1139/cjes-2017-0077

——— 2020. Results of the 2014–2017 drilling programs on the Niagara Peninsula: Graphic logs, descriptions and analytical data; Ontario Geological Survey, Miscellaneous Release—Data 383.

Burt, A.K. and Bajc, A.F. 2020. A regional stratigraphic framework for hydrogeologic studies above the Niagara Escarpment in southern Ontario; *in* Regional-scale groundwater geoscience in southern Ontario: An Ontario Geological Survey, Geological Survey of Canada, and Conservation Ontario Geoscientists Open House; Ontario Geological Survey, Open File Report 6361, 46p.

Burt, A.K. and Dodge, J.E.P. 2011. Three-dimensional modelling of surficial deposits in the Barrie–Oro moraine area of southern Ontario; Ontario Geological Survey, Groundwater Resources Study 11, 125p.

——— 2016. Three-dimensional modelling of surficial deposits in the Orangeville–Fergus area of southern Ontario; report *in* Ontario Geological Survey, Groundwater Resources Study 15, 155p.

Conway-White, O., Steelman, C.M., Smiarowski, A., Ugalde, H., Endres, A.L., Arnaud, E. and Parker, B.L. 2022. Improving spatial characterization of buried bedrock valleys through airborne frequency-domain electromagnetic, residual magnetic, and surface resistivity measurements; Journal of Applied Geophysics, v.199, paper 104584. doi.org/10.1016/j.jappgeo.2022.104584

Gao, C., Shirota, J., Kelly, R.I., Brunton, F.R. and van Haaften, S. 2006. Bedrock topography and overburden thickness mapping, southern Ontario; Ontario Geological Survey, Miscellaneous Release—Data 207.

Greenhouse, J.P. and Karrow, P.F. 1994. Geological and geophysical studies of buried valleys and their fills near Elora and Rockwood, Ontario; Canadian Journal of Earth Sciences, v.31, p.1838-1848.

Hamilton Region Conservation Authority 2020. Lafarge 2000 trail - 2019 management plan. A joint project of The City of Hamilton and The Hamilton Region Conservation Authority; Hamilton Conservation Authority, draft 2020, 36p.

Karrow, P.F. 1963a. Pleistocene geology of the Hamilton–Galt area; Ontario Department of Mines, Report 16, 68p.

——— 1963b. Pleistocene geology of the Galt area, southern Ontario; Ontario Department of Mines, Map 2029, scale 1:63 360.

——— 1963c. Pleistocene geology of the Hamilton area, southern Ontario; Ontario Department of Mines, Map 2033, scale 1:63 360.

——— 1968a. Pleistocene geology of the Guelph area; Ontario Department of Mines, Report 61, 38p.

——— 1968b. Pleistocene geology of the Guelph area, southern Ontario; Ontario Department of Mines, Map 2153, scale 1:63 360.

——— 1987a. Quaternary geology of the Hamilton–Cambridge area, southern Ontario; Ontario Geological Survey, Report 255, 94p.

——— 1987b. Quaternary geology, Cambridge area, southern Ontario; Ontario Geological Survey, Map 2508, scale 1:50 000.

——— 1987c. Quaternary geology, Hamilton area, southern Ontario; Ontario Geological Survey, Map 2509, scale 1:50 000.

Marich, A.S., Priebe, E.H., Bajc, A.F., Rainsford, D.R.B. and Zwiers, W.G. 2011. A geological and hydrogeological investigation of the Dundas buried bedrock valley, southern Ontario; Ontario Geological Survey, Groundwater Resources Study 12, 248p.

Ministry of Natural Resources and Forestry 2022. Ontario digital terrain model (Lidar-derived); Ministry of Natural Resources and Forestry, Provincial Mapping Unit, Peterborough, Ontario, available on Ontario GeoHub [accessed November 23, 2022].

Mulligan, R.P.M. 2020. Quaternary stratigraphy and hydrogeology in Central Simcoe County; *in* Regional-scale groundwater geoscience in southern Ontario: An Ontario Geological Survey, Geological Survey of Canada, and Conservation Ontario Geoscientists Open House; Ontario Geological Survey, Open File Report 6361, 46p.

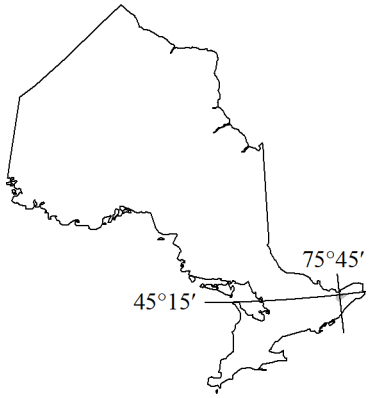
Ontario Geological Survey 2010. Surficial geology of southern Ontario; Ontario Geological Survey, Miscellaneous Release—Data 128 – Revised.

——— 2013. Ontario geophysical surveys, ground gravity data, grid and point data (ASCII and Geosoft® formats) and vector data, Orangeville area; Ontario Geological Survey, Geophysical Data Set 1072.

——— 2014. Ontario geophysical surveys, ground gravity data, grid and point data (ASCII and Geosoft® formats) and vector data, Niagara area; Ontario Geological Survey, Geophysical Data Set 1073.

Steelman, C.M., Arnaud, E., Pehme, P. and Parker, B.L. 2018. Geophysical, geological, and hydrogeological characterization of a tributary buried bedrock valley in southern Ontario; Canadian Journal of Earth Sciences, v.55, p.641-658. doi.org/10.1139/cjes-2016- 0120

25. Project SO-22-006. South Ottawa Groundwater Study, Eastern Ontario



T. Di Iorio[1], S. Foubister[1] and C.N. Bocking[2]

[1]Infrastructure and Water Services Department, City of Ottawa, Ottawa, Ontario K1P 1J1
[2]Earth Resources and Geoscience Mapping Section, Ontario Geological Survey, Sudbury, Ontario P3E 6B5

INTRODUCTION

Development in rural communities is typically dependant on private servicing (groundwater wells) as a source of drinking water. Natural groundwater quality in exceedance of Provincial Drinking Water Standards, Objectives and Guidelines (Ministry of the Environment 2006) is a common issue that can limit development on private services in eastern Ontario. Aquifers capable of supporting privately serviced developments have not been mapped at a scale that is practical for municipalities to screen the development potential of a property or create land use zoning maps. Consequently, municipalities in eastern Ontario, namely the United Counties of Prescott and Russell and the City of Ottawa, have identified a need for an Aquifer Capability Screening Tool (ACST) with respect to groundwater resource use.

An ACST consists of maps outlining areas of expected groundwater quality and quantity to assist in evaluating the development potential of a property where private wells are proposed. The ACST does not replace the need for local-scale studies to support development proposals, but provides the municipality and local developers information to help pre-screen development applications, scope hydrogeological studies and inform land use zoning decisions.

Following a regional groundwater sampling study carried out in eastern Ontario by the Ontario Geological Survey (OGS) as part of the Ontario Ambient Groundwater Geochemistry Program (AGGP) in 2012 (Freckelton and Hamilton 2012), 4 groundwater mapping studies were completed in partnership with the OGS to support the development of ACSTs in eastern Ontario municipalities (Figure 25.1). An ACST has been developed for the City of Clarence–Rockland (pilot study, 2013–2016) (Morton et al. 2013; Morton 2015; Geofirma Engineering Ltd. 2016), the Township of Alfred and Plantagenet (2015–2017) (Di Iorio, Lemieux and Hamilton 2015; Morrison Hershfield 2017), East Ottawa (2017–2020) (Di Iorio et al. 2017; Morrison Hershfield 2020), and an ACST is being developed for West Ottawa (2019–present) (Di Iorio et al. 2019). Geochemical data have been collected within the Township of Champlain (Di Iorio et al. 2017) and a mapping study will be completed in the future. The area for the current study is located within the southern rural portion of the City of Ottawa (approximate area 1050 km^2), where various groundwater quality issues exist. The South Ottawa Groundwater Study is intended to complete the sampling and mapping program throughout rural Ottawa.

Ambient groundwater quality issues in eastern Ontario are linked to the geological setting and are largely the result of the marine environment that existed in the St. Lawrence Lowland following the most recent glacial retreat. In addition to trapping saline water, marine clays mask a complex Paleozoic bedrock topography and geology, the interbedded limestone and shale units of which, along with long

Summary of Field Work and Other Activities, 2022,
Ontario Geological Survey, Open File Report 6390, p.25-1 to 25-9.

© King's Printer for Ontario, 2022

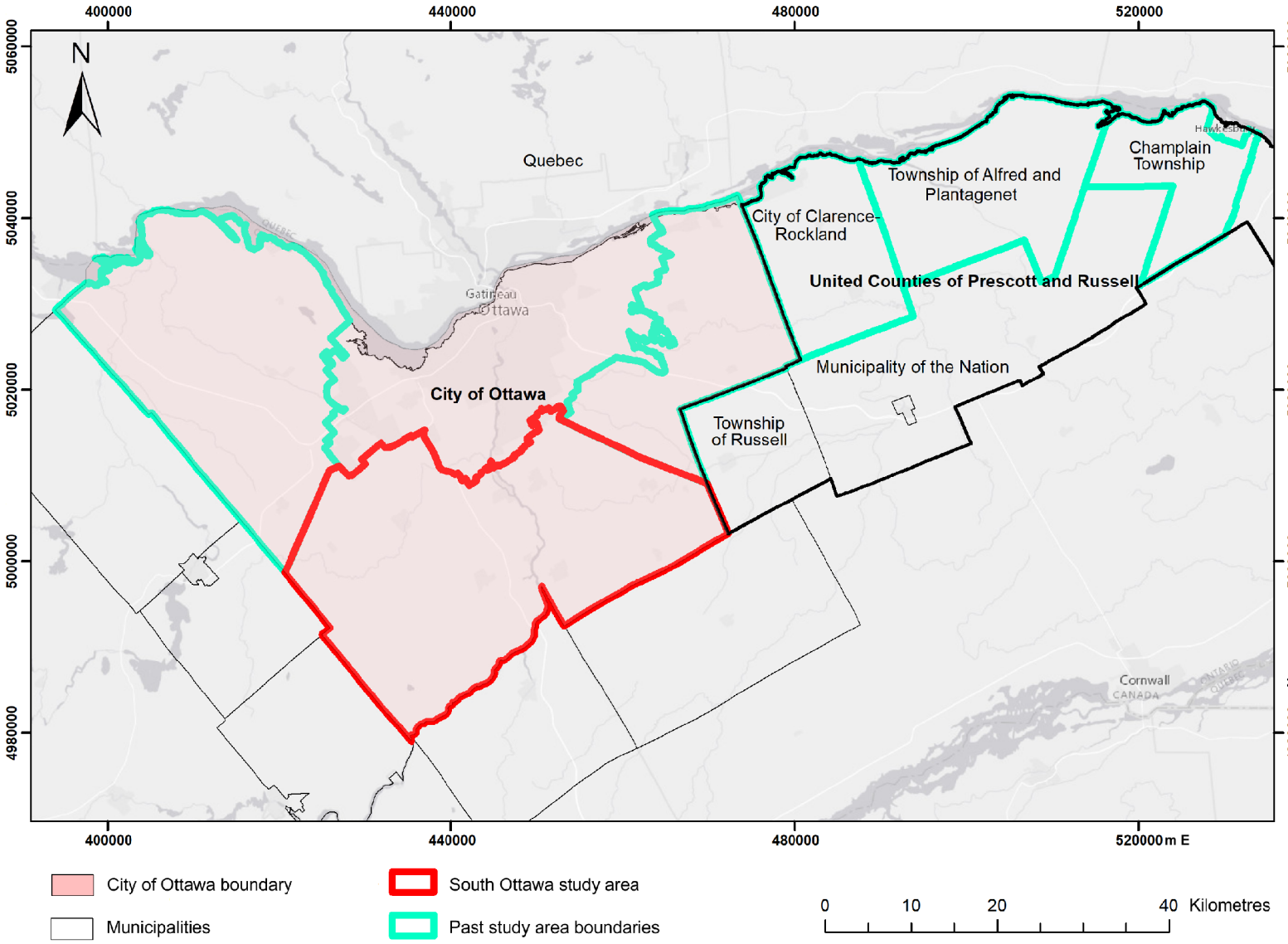


Figure 25.1. Eastern Ontario Aquifer Capability Screening Tool study area boundaries: City of Clarence–Rockland (pilot study, 2013–2015); Township of Alfred and Plantagenet (2015–2016); East Ottawa (2017–2019); Champlain Township (2017–2019); West Ottawa (2019–2022); South Ottawa (2022–present). Universal Transverse Mercator (UTM) co-ordinates provided using North American Datum 1983 (NAD83) in Zone 18.

groundwater residence times, may further contribute to poor water quality. Within the southern part of the City of Ottawa, groundwater quality issues may also be attributed to anthropogenic sources (i.e., road salt, septic systems, agricultural application of nutrients, etc.), which are more prevalent in areas of thin overburden over bedrock and areas with karstic bedrock formations.

The City of Ottawa completed city-wide groundwater geochemistry analyses (Colgrove 2016) using the geochemical sampling data obtained from the Ontario AGGP (Freckelton and Hamilton 2012; Hamilton 2015). The analyses identified different groundwater quality issues related to conditions across the City based on physical controls, flow regime and residency time, dominant chemical processes, and typical chemistry. Within southern rural Ottawa, 3 distinct groundwater chemistry regimes were identified: 1) areas of thin to absent overburden with near surface bedrock, characterized by low total dissolved solids, neutral pH with potential for anthropogenic chloride, sodium, nitrate and bacteria, located within the south and western portions of the proposed study area; 2) intermediate bedrock (not a valley or depression), found throughout the study area as a transitional zone between bedrock valleys and areas of elevated bedrock, characterized by moderate total dissolved solids with elevated salinity; and 3) areas with clear anthropogenic effects found within the central and eastern portion of the study area, with elevated total dissolved solids, mineralized water and elevated sodium and chloride. The groundwater geochemistry issues related to these hydrogeological settings will be further investigated by the current study.

In addition, parts of the south Ottawa study area are characterized as hydrogeologically sensitive in regard to private wells because about 33% of the proposed study area has less than 2 m of overburden and about 10% of the area is mapped as known, potential or inferred karst (Brunton and Dodge 2008). Hydrogeological sensitivity was investigated as part of the West Ottawa Groundwater Study (Di Iorio et al. 2019) and the investigation will continue in the current study of south Ottawa, specifically issues and risks related to development relying on private wells in these areas. This will help inform future planning decisions related to development in hydrogeologically sensitive areas.

The current study consists of a field program to collect high-quality geochemistry data at a refined scale across southern rural Ottawa (data density: 1 to 2 samples per 2 km^2), in order to map local aquifers, define hydrostratigraphy, and determine groundwater age and flow patterns to enhance the development of an ACST. Analysis of this information will broaden the understanding of groundwater within the former Champlain Sea basin in the St. Lawrence Lowland.

The field methods outlined below reflect the work undertaken by the City of Ottawa and the OGS toward the collection and measurement of groundwater samples from private residential wells across southern rural Ottawa.

METHODS

Site Selection

Site selection generally followed the methodology developed for the Ontario AGGP (Hamilton, Brauneder and Mellor 2007). The methodology applies a grid across the project area to ensure samples are collected at a regular spacing. For this study, samples were collected on a 2 km grid across southern rural Ottawa, providing a resolution finer than the Ontario AGGP, which uses a 10 km grid. The goal for the current study was to sample 1 bedrock well from each grid block and 1 overburden well from every 2 grid blocks: this distribution maximizes data collection from bedrock wells. An assessment of well chemistry from the previous ACST studies in eastern Ontario revealed that the shallow overburden wells (dug or bored) were reflective of local property-scale conditions and not typically representative at the

ACST mapping scale and, consequently, the ACST development is dependent on reliable bedrock chemistry. Note that about a third of the study area has soil thickness less than 2 m and no dug wells are expected in those areas. The sampling grid and distribution of wells sampled are shown in Figure 25.2.

Site selection was initiated prior to the start of sampling in order to expedite the sampling season (17 weeks between June and September) and to raise awareness about the project in the community. Project advertising was divided into 2 phases because of the large size of the study area: advertising in the eastern half took place in late May and in the western half in early July. A one-page flyer (in English and French) was designed to introduce the project and solicit volunteers for well sampling. The flyer was displayed as posters in public areas, such as libraries, community centres, grocery stores and gas stations, and delivered as a directed mail drop to 26 500 rural residents across southern rural Ottawa. In addition, advertisements were run in several local newspapers and social media platforms throughout the summer.

Site scheduling protocols developed for the Clarence–Rockland Groundwater Sampling Program were applied for this study (Morton et al. 2013). First, a sampling schedule was developed for the 17 week field season corresponding to the sampling grid. Volunteers contacted project staff by telephone or email. Volunteers were scheduled if they met specific criteria, including availability of a well record, access to the well and access to a tap that provided untreated groundwater. To simplify site scheduling, it was assumed that drilled wells were bedrock wells and dug wells were overburden wells. This assumption holds true for overburden wells in this region and, based on local Ministry of the Environment, Conservation and Parks (MECP) water well records, is generally true for bedrock wells. The few discrepancies found will be corrected during the post-field quality control and audit of all station data. Site scheduling was conducted on a first-come-first-served basis for suitable wells. If a volunteer phoned and another volunteer had previously been scheduled for that well type and grid block, then the well was not sampled; however, volunteer information was added to a waiting list for future consideration.

As a result of advertising the project, approximately 1420 residents in southern rural Ottawa volunteered to participate in the well sampling program; consequently, 160 sites met the criteria for sampling and were pre-scheduled. In grid blocks where no residents volunteered to be part of the study, the field team would select wells to sample at random by going door-to-door within the grid block. Soliciting volunteers door-to-door was time consuming and not always successful. Residents who had previous knowledge of the project (i.e., through newspaper ads, flyers, posters or neighbours) were more likely to participate when approached.

At the end of the field season, after all the grid blocks were searched for well volunteers, an additional 35 wells were sampled in locations of interest. Locations of waiting-list well volunteers were entered into a geographic information system (GIS) interactive map to facilitate the selection of additional well sampling locations. Additional wells were selected in areas of varied bedrock geology, areas where spatial distribution could be enhanced, and areas where elevated parameters (such as radon, dissolved oxygen or methane) were identified in the field parameter or preliminary analytical results. Finally, additional wells were sampled within villages with increased development pressures.

Field Sampling

Field sampling was carried out in general accordance with the protocols developed by the Ontario Geological Survey (OGS) in their Ontario Ambient Groundwater Geochemistry Project (Hamilton, Brauneder and Mellor 2007; Hamilton and Brauneder 2008).

Site visits started with the well owner signing a consent form and completing a brief well owner interview. Interviews included questions about the age and depth of the well, a description of water use and water treatment systems, and historic water quality or quantity issues. Following the interview,

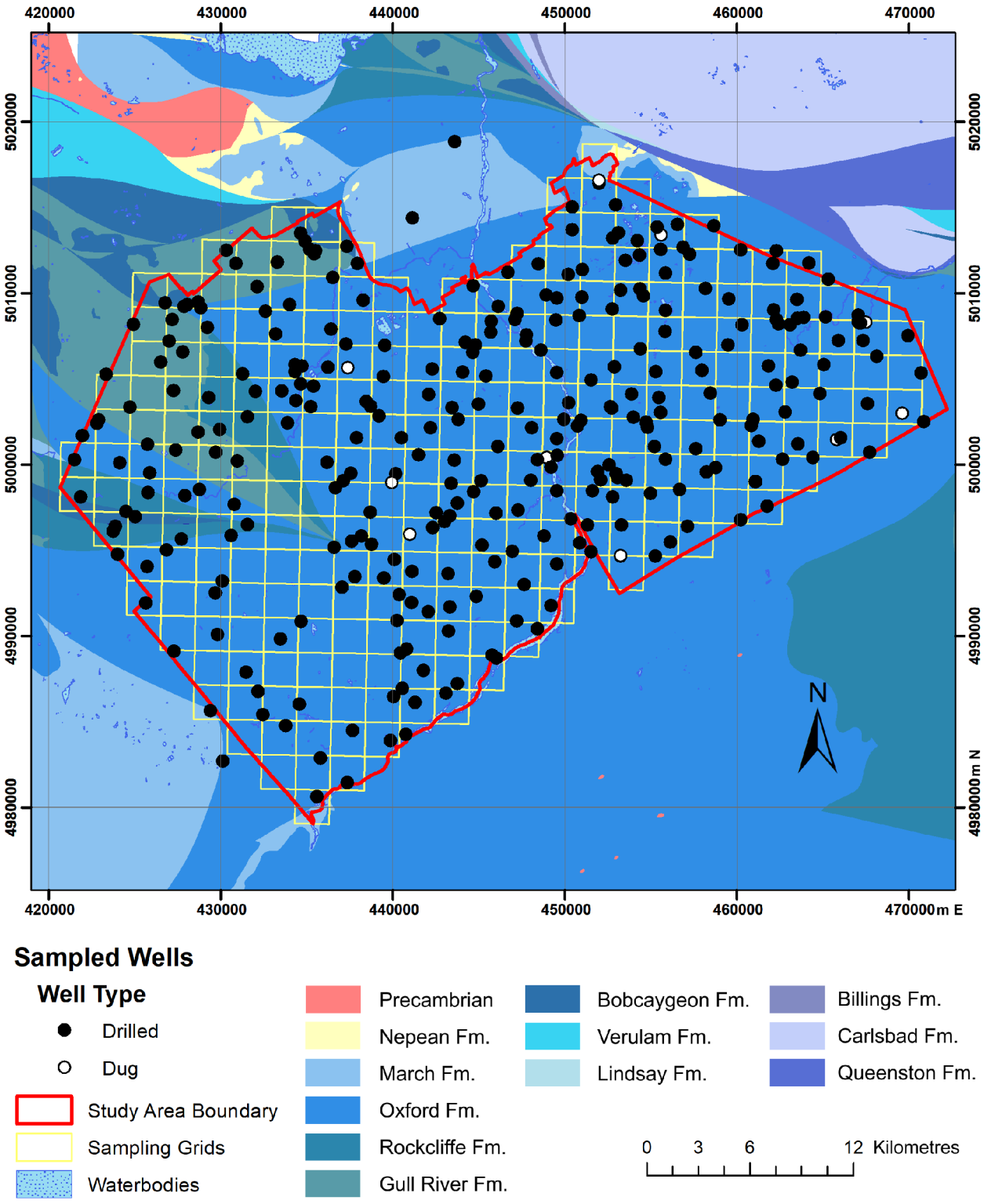


Figure 25.2. Southern rural Ottawa study area boundary, bedrock geology and sample locations. Fine mesh shows the 2 km by 2 km grid blocks, within which ideally 1 bedrock well would be sampled for each grid block and 1 overburden well would be sampled for every 2 grid blocks. Bedrock geology *from* Armstrong and Dodge (2007). All UTM co-ordinates provided using NAD83 in Zone 18. Paleozoic stratigraphic units are listed from oldest to youngest (top to bottom, and left to right), i.e., from NepeanFormation ("Fm.") to Gull River, Bobcaygeon to Lindsay, and Billings to Queenston formations.

a visual inspection and measurements were taken at the wellhead, including casing diameter, stick-up, water level and well depth and location (Universal Transverse Mercator (UTM) co-ordinates using a Garmin GPSMap® 60Cx global positioning system).

A water-sampling apparatus was connected to a faucet that provided untreated water. Water was purged prior to sample collection. During the initial water purging and throughout sample collection, water was run through a flow cell containing a YSI™ multi-parameter probe (YSI EXO 1) to log and record measurements of temperature, pH, conductivity, oxidation–reduction potential (ORP) and dissolved oxygen. Sampling started once stable temperature and pH readings were observed on the YSI™ multi-parameter probe. This typically occurred after 2 garbage pails had been purged (about 240 L). Sixteen sample bottles were filled at each site for metals, anions, mercury, iodide, isotopes, tritium, dissolved organic carbon (DOC) (2 bottles), total Kjeldahl nitrogen + ammonia + nitrate + nitrite +colour, methane, bacteria, artificial sweeteners, radon (2 bottles), gross alpha/beta, and a 'spare' sample bottle for additional analysis if needed. The sample bottles for metals, anions, mercury and DOC (1 bottle) were each filled using a syringe and a 0.45 μm filter.

Alkalinity was measured on site by titrating 1.6 N H_2SO_4 into 100 mL of sample with an added indicator packet of bromocresol green-methyl red. Titrated amounts were recorded at 3 endpoints: blue grey, violet grey and pink. Hydrogen sulphide (H_2S) content was measured on site by preparing a blank of de-ionized water and comparing it to a prepared sample via a colour wheel. Hydrogen sulphide was not measured at sites where oxygen was present and ORP was positive, as it was reasonable to assume that H_2S would not be present. Water samples for bacterial analyses were obtained directly from the faucet, following disinfection of the faucet.

At the end of each field day, bottles were dropped off, along with a Chain of Custody form, at the City of Ottawa laboratory at the Robert O. Picard Environmental Centre for immediate measurement (total Kjeldahl nitrogen + ammonia + nitrate + nitrite + colour, DOC (unfiltered), bacteria, radon (2 bottles), gross alpha/beta). The sample bottles for radon and gross alpha/beta were shipped the next day to SRC Laboratories for analyses; the remaining analyses were conducted at the City of Ottawa laboratory. Methane, isotopes and tritium bottles were stored at room temperature, artificial sweetener bottles were stored in a freezer and all other samples were refrigerated. Methane samples were measured the following morning, iodide was measured within 5 days, and all other samples were stored and sent to the OGS Geoscience Laboratories at various times throughout the field season.

Measurement Probes and Calibration

A YSI™ EXO 1 multi-parameter data logging instrument was used to continuously record pH, electrical conductivity, temperature, ORP and dissolved oxygen. The instrument was connected to a sonde that incorporated 3 probes: pH and ORP; temperature and electrical conductivity; and dissolved oxygen.

At the start of each sampling day, the YSI™ probe was calibrated daily for pH, electrical conductivity and dissolved oxygen. The pH probe was calibrated using a 3-point calibration at pH of 4, 7 and 10; electrical conductivity was checked with a 1413 μS/cm solution and calibrated when required, and the optical dissolved oxygen probe was calibrated daily to zero-oxygen standard solution and water sample with 100% oxygen. The oxidation–reduction potential was checked weekly against an ORP standard solution of +250 mV and calibrated if required.

Methane Measurements

Methane (CH_4) was measured every morning for samples that were collected from the previous day. Gas contents of CH_4, oxygen (O_2) and carbon dioxide (CO_2) were measured using an RKI Eagle™ Portable Multi-Gas Meter, and temperature was measured using a hand-held mercury thermometer. Methane measurements were made using 2 sensors: a low-level sensor capable of measuring from 0 to 25 000 ppm CH_4, and a high-level sensor capable of measuring up to 50 volume % CH_4.

The RKI Eagle™ was checked daily prior to methane measurement for low-level methane and carbon dioxide and monthly for high-level methane; the instrument was calibrated for methane and carbon dioxide when required. Low-level methane was calibrated using a 25 000 ppm CH_4 gas cylinder; high-level methane was calibrated using a 50.0 volume % CH_4 gas cylinder; and CO_2 was calibrated using a 2.50 volume % CO_2 cylinder.

Iodide Measurements

The Iodide Ion Selective Electrode (Orion model 9453BN) was connected and operated through an Orion Five-Star (A324) meter. The meter was calibrated to 10 ppb and 1000 ppb prior to measurement. Iodide samples were measured within 5 days of their collection. Prior to measurement, the neck-space (2 mL) of each sample was discarded, and 1 mL of ionic strength adjuster and 1 magnetic stir bar were added. The probe was inserted into the sample bottle over top of a magnetic stirring plate and a measurement was recorded after 5 minutes.

Radon Samples

Sampling and analysis of radon and gross alpha/beta were included as part of the current South Ottawa Groundwater Study and the West Ottawa Groundwater Study (Di Iorio et al. 2019), although these parameters were not included in the previous eastern Ontario groundwater mapping studies. Data will be used to help validate maps of radon potential in the Ottawa area, in partnership with Health Canada. Radon and gross alpha/beta were sampled at each site and sent to SRC Laboratories for analyses.

RESULTS

A total of 381 samples were submitted for geochemical analysis from the field program. Groundwater was sampled from private residential wells at 327 locations within southern rural Ottawa. Of the 327 wells sampled, 317 were bedrock wells and 10 were shallow overburden wells. The remaining 54 sample sets sent for analysis included 29 standards, 6 blanks and 19 duplicates.

Every grid block in the study area boundary was explored; however, data gaps exist where grid blocks did not contain wells, which is typical in agricultural areas, forested areas and wetlands with no development. Approximately a third of the study area has soil thickness less than 2 m, where dug wells cannot be installed, thus only drilled wells were sampled in those areas. In general, dug wells are not typically found in the study area because of the shallow bedrock and favourable water quality in the bedrock aquifers. A database of field data has been maintained throughout the field season. Field data were reviewed during the field season and additional bedrock wells were sampled in areas where anomalies were identified to help identify the extent of these anomalies for parameters such as elevated dissolved oxygen, methane and/or radon. Additional bedrock wells were also sampled in villages where development pressures are greater, thereby augmenting the ACST.

Laboratory results for the geochemical data are still pending at the time of writing. Once the complete suite of geochemical parameters are available, individual analytical reports will be prepared and mailed to each of the well owners that participated in the project. Information collected at each site will undergo a thorough data audit and quality control assessment. Analytical results will be used to help produce maps of groundwater quality, which will be used to develop an ACST for the City of Ottawa.

ACKNOWLEDGMENTS

We would like to start by acknowledging the extraordinary contributions of Dr. Stewart Hamilton who initiated the Ontario Ambient Groundwater Geochemistry Program (AGGP) in 2007. Dr. Hamilton organized and managed many years of groundwater geochemical sampling across Ontario, through the Ontario Geological Survey (OGS), which resulted in the development of a practical and reliable province-wide groundwater database. Several geoscientific discoveries resulted from the program, as well as numerous university theses and papers. We are thrilled that eastern Ontario was able to be a part of Ontario AGGP (starting in 2013) and benefit from the tremendous direction and insight of Dr. Hamilton.

We would like to thank the City of Ottawa and the OGS for providing funding for this project. We extend our sincerest appreciation to the hard-working and always-keen field team: Kyra Kinsman, Kristen McDonald and Lucas McPhail. Thank you to Jeremy Creppin at the OGS for providing assistance related to the field program. We would also like to thank City of Ottawa staff at the Robert O. Picard Environmental Centre, who allowed the use of the facilities and provided support during the sampling program; thank you to Jennifer Donaldson who organized the daily lab samples at the City of Ottawa labs. Thank you to Alycia White-Brown and the business support staff at the City of Ottawa for their exceptional support in advertising the field program. We also extend our sincere appreciation to Paula Palazzo for the endless administrative support throughout the field season. Finally, we would like to thank all the residents across southern rural Ottawa who volunteered to be part of the sampling program; we were happy that so many residents were eager to learn more about their groundwater resources and took time to share their experiences and insights.

REFERENCES

Armstrong, D.K. and Dodge, J.E.P. 2007. Paleozoic geology of southern Ontario; Ontario Geological Survey, Miscellaneous Release—Data 219.

Brunton, F.R and Dodge, J.E.P. 2008. Karst of southern Ontario and Manitoulin Island; Ontario Geological Survey, Groundwater Resource Study 5.

Colgrove, L.M. 2016. Groundwater geochemistry in the City of Ottawa: A regional picture; unpublished report prepared for the City of Ottawa, 79p.

Di Iorio, T., Harrison, R.A., Al., T., Majury, A. and Hamilton, S.M. 2019. West Ottawa groundwater study; *in* Summary of Field Work and Other Activities, 2019, Ontario Geological Survey, Open File Report 6360, p.23-1 to 23-9.

Di Iorio, T., Lemieux, A.J. and Hamilton, S.M. 2015. Township of Alfred and Plantagenet groundwater study; *in* Summary of Field Work and Other Activities, 2015, Ontario Geological Survey, Open File Report 6313, p.38-1 to 38-6.

Di Iorio, T., Melaney, M., Foubister, S. and Hamilton, S.M. 2017. East Ottawa–Champlain groundwater study; *in* Summary of Field Work and Other Activities, 2017, Ontario Geological Survey, Open File Report 6333, p.27-1 to 27-8.

Freckelton, C.N. and Hamilton, S.M. 2012. Ambient Groundwater Geochemistry Project of the Ottawa–St. Lawrence River area; *in* Summary of Field Work and Other Activities, 2012, Ontario Geological Survey, Open File Report 6280, p.37-1 to 37-7.

Geofirma Engineering Ltd. 2016. Clarence-Rockland groundwater study: Development of an Aquifer Capability Screening Tool; unpublished report, Geofirma Engineering Ltd., 144p.

Hamilton, S.M. 2015. Ambient groundwater geochemistry data for southern Ontario, 2007–2014; Ontario Geological Survey, Miscellaneous Release—Data 283 – Revised.

Hamilton, S.M. and Brauneder, K. 2008. The Ambient Groundwater Geochemistry Project: Year 2; *in* Summary of Field Work and Other Activities, 2008, Ontario Geological Survey, Open File Report 6226, p.34-1 to p.34-7.

Hamilton, S.M., Brauneder, K. and Mellor, K.J. 2007. The Ambient Groundwater Geochemistry Project – southwestern Ontario; *in* Summary of Field Work and Other Activities, 2007, Ontario Geological Survey, Open File Report 6213, p.20-1 to 20-9.

Ministry of the Environment 2006. Technical support document for Ontario Drinking Water Standards, Objectives and Guidelines; Ministry of the Environment, Toronto, Ontario, Public Information Banking System (PIBS) 4449e01, 40p.

Morrison Hershfield 2017. Development of an Aquifer Capability Screening Tool, Township of Alfred and Plantagenet; unpublished report, Morrison Hershfield, 53p.

——— 2020. Development of an Aquifer Capability Screening Tool, East Ottawa, City of Ottawa, Ontario; unpublished report, Morrison Hershfield, 86p.

Morton, S.R. 2015. Development and evaluation of an aquifer capability screening tool. Pilot study: Clarence–Rockland, Ontario; unpublished MSc thesis, University of Ottawa, Ottawa, 113p.

Morton, S.R., Di Iorio, T., Hamilton, S.M. and Robin, M.J.L. 2013. Development of an aquifer mapping tool, City of Clarence–Rockland, Ontario; *in* Summary of Field Work and Other Activities, 2013, Ontario Geological Survey, Open File Report 6290, p.40-1 to 40-7.

This page left blank intentionally

Geoscience Laboratories

26. Osmium Analysis at the Geoscience Laboratories by Nickel Sulphide Fire Assay with Inductively Coupled Mass Spectrometric Finish



O.M. Burnham[1]

[1]Geoscience Laboratories, Ontario Geological Survey

INTRODUCTION

Since it was originally established at the Geoscience Laboratories (Geo Labs), the nickel sulphide (NiS) fire assay method with inductively coupled plasma mass spectrometric (ICP–MS) finish (method code IMP-200, Richardson and Burnham 2002) has only reported 5 of the 6 platinum group elements: ruthenium (Ru), rhodium (Rh), palladium (Pd), iridium (Ir) and platinum (Pt). The sixth platinum group element, osmium (Os), was not reported because of its problematic chemistry and difficulties in creating a stable matrix-matched calibration solution. In response to several client requests for the inclusion of osmium in the IMP-200 method, in March 2021, experiments were undertaken to determine ways of stabilizing the analyte, allowing it to be added to the method. This article outlines the results of these experiments, summarizes modification of the instrumental method to include osmium in the analytes measured, and documents the capabilities of the IMP-200 method for osmium analysis.

CALIBRATION

Under oxidizing conditions, such as those encountered during the preparation and analysis of the precious metals after NiS fire assay, osmium in solution can be easily oxidized from the soluble hexachloroosmate complex to a volatile tetraoxide (OsO_4) leading to several significant challenges for analysis:

- Because of its volatility at room temperature (boiling point OsO_4 = 130°C), OsO_4 can be easily lost by evaporation if solutions are left open to the air for any length of time (e.g., while awaiting analysis on the autosampler). Where the Os loss is from sample solutions, this can lead to low recoveries and under-estimation of sample osmium contents. When or if the osmium loss is from calibration solutions, this can lead to an apparent decrease in sensitivity and so an over-estimation of osmium contents.
- When solutions containing oxidized osmium are introduced to an ICP–MS or other instruments by conventional solution nebulization, volatile OsO_4 can be preferentially transported to the plasma, enhancing sensitivity. Whereas this can and has been used to enhance sensitivity (e.g., Bazan 1987; Richardson et al. 1989; Gregoire 1990), inaccurate results will be obtained if the degree of oxidation in sample and calibration solutions is not matched.
- OsO_4 can be highly "sticky" within the sample introduction system (e.g., probe line, pump tubing, mixing valves, nebulizer, spray chamber and injector), leading to significant carryover between analyses.

Summary of Field Work and Other Activities, 2022,
Ontario Geological Survey, Open File Report 6390, p.26-1 to 26-9.

© King's Printer for Ontario, 2022

A combination of these behaviours was clearly visible in the raw and internal standard-normalized intensities for osmium in the simple 60 ppb calibration solution made up from hexachloroosmate stock solution in the 4% v/v HNO_3 – 4% v/v HCl acid matrix used for samples that was initially used for testing, including the following:

- Considerably slower wash out than the other precious metals, the osmium signal taking 30 minutes (or more than 6 analyses) to drop to less than twice the baseline. Whereas a much more concentrated solution of platinum taking only 2 analyses (10 minutes) for the same decrease (Figure 26.1).
- Over the course of a single 18-hour run, the ratio of the osmium intensities to those of 205-thallium (added to the calibration solution as an internal standard) decrease by 20%, most likely as a result of the volatile loss of OsO_4 created by oxidation of the Os(IV) in the stock solution, whereas those for the other heavy precious metals in a similar concentration solution show no substantial change (Figure 26.2).
- Over longer time periods, the decrease in Os:^{205}Tl ratios is even more pronounced. Even without use, over the period of a month, the Os:^{205}Tl ratios for an individual calibration solution decreased to less than 10% of its original value and, over a year, decreased to less than 1% of its original value (Figure 26.3A). Over the same periods, the instrument control solutions showed no such drift and little variation (Figure 26.3B), indicating greater stability of osmium in the more complex matrix.
- When very fresh (i.e., on the day of preparation), calibration solutions made up from hexachloroosmate stock solution added to the simple acid matrix appeared to give highly elevated Os:^{205}Tl ratios that decreased over a matter of days.

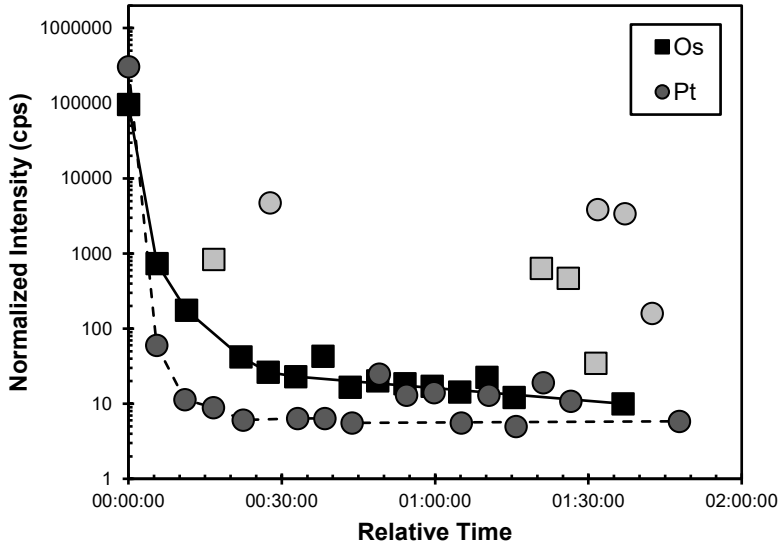


Figure 26.1. Thallium-normalized intensity of $^{189}OsO_2^+$ and $^{195}Pt^+$ illustrating the slow washout of 60 ppb Os calibration solution made up from hexachloroosmate stock solution in 4% v/v HNO_3 – 4% v/v HCl matrix. Black symbols: acid and/or method blank solutions. Grey symbols: osmium- and platinum-bearing instrument control solutions.

Given the greater stability of osmium in the instrument control solutions, in March 2021, a set of 60 ppb Os calibration solutions were made up in a variety of matrices, including the 4%–4% v/v HNO_3–HCl sample acid matrix, a matrix of 4% v/v HCl only, and a blend of previously analyzed procedural blanks, each with and without the addition of $SnCl_2$ as a reducing agent to stabilize any Os(VIII) present. These solutions were then analyzed over a period of 11 months to monitor their stability using their measured Os:^{205}Tl ratios (Figure 26.4). Only the solutions prepared in the procedural blank matrix showed a near-steady ratios. Given the apparent success of the calibration solution prepared in the procedural blank matrix, in August 2021, it was adopted for the calibration of osmium during production analyses.

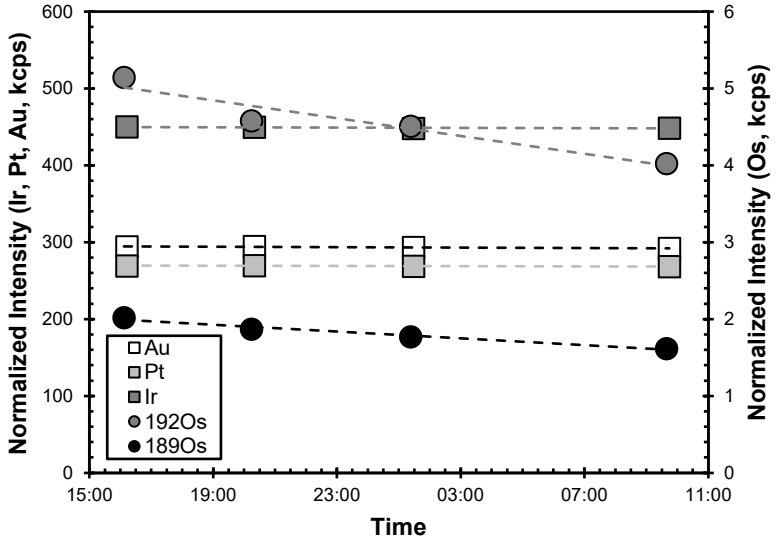


Figure 26.2. Decrease in thallium-normalized ^{189}Os, ^{192}Os, ^{197}Au, ^{195}Pt and ^{193}Ir intensities as a function of time (in hours) within a single run using 60 ppb calibration solutions produced by the direct addition of hexachloroosmate or multi-element stock solutions to a 4% v/v HNO_3 – 4% v/v HCl matrix.

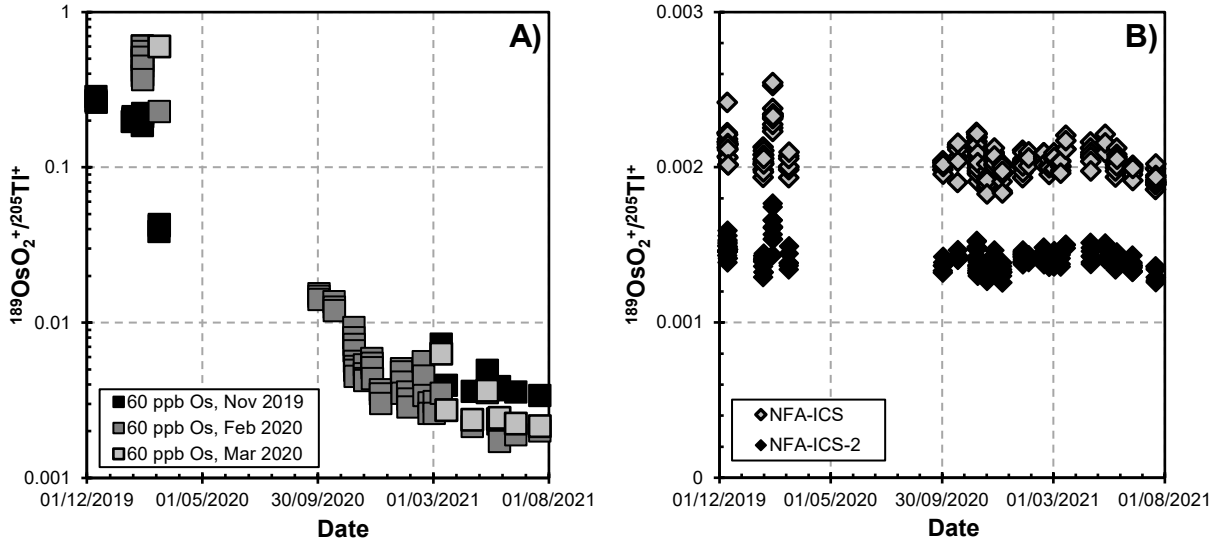


Figure 26.3. Change in $^{189}OsO_2^+$:$^{205}Tl^+$ ratio for **A**) 60 ppb Os calibration solutions made up from hexachloroosmate stock solution added to a 4% v/v HNO_3 – 4% v/v HCl matrix and **B**) instrument control solutions prepared from processed sample solutions. Data shown over 20 months, from December 2019 to August 2021.

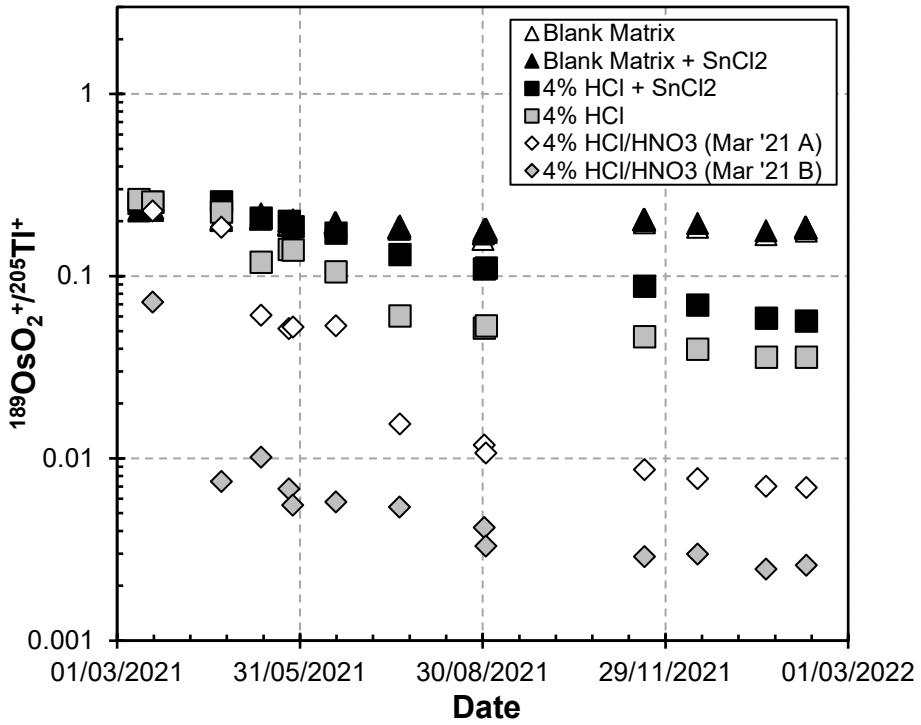


Figure 26.4. Change in $^{189}OsO_2^+$:$^{205}Tl^+$ ratio for 60 ppb Os calibration solutions made up from hexachloroosmate stock solution in different matrices. Data shown over 12 months, from March 2021 to March 2022.

Table 26.1. Intensities of osmium atomic and molecular ions in 60 ppb stock solutions measured by ICP-QQQ-MS in O_2 mode.

Analyte Ion	Q1	Q2	Absolute Intensity	Relative Intensity[a]
Os^+	189	189	28564	100%
OsO^+	189	205	6956	24%
OsO_2^+	189	221	82832	290%

[a] *Normalized to intensity of atomic ion.*

INSTRUMENTAL PARAMETERS

At the same time as initial work was being conducted on the stabilization of calibration solutions, the optimum instrumental parameters required for its analysis on the Agilent Technologies, Inc. triple-quadrupole inductively coupled mass spectrometer (ICP-QQQ-MS) were established. Although no data were given for osmium, literature data for the reactions of the allied element Ru during ICP-QQQ-MS analysis in different modes (Sugiyama and Nakano 2014) indicated that a suitable approach might be to analyze osmium in O_2-mode (pressurizing the cell with a slow flow of oxygen gas) along with the other heavy precious metals (iridium, platinum and gold), measuring the analyte either on-mass or as the monoxide ion with a mass shift of 16 amu (Table 26.1). Although this was expected to give poorer sensitivity than analyzing osmium on-mass with the cell unpressurized and, unlike platinum and gold, analysis in O_2-mode was not needed to remove potential interferences[2], it was viewed as being more time-efficient to analyze all the heavy precious metals in the same mode. Experimentation with osmium stock

[2] *Whereas $^{176}HfO^+$, $^{179}HfO^+$, $^{180}WO^+$, and $^{181}TaO^+$ have the potential to interfere with $^{192}Os^+$, $^{195}Pt^+$, $^{196}Pt^+$ and $^{197}Au^+$, respectively, because of their high oxygen-atom affinity (≥127 kcal/mol: Koyanagi and Bohme 2001) and/or potential presence as acid contaminants, the effect of $^{173}YbO^+$ and $^{174}YbO^+$ on $^{189}Os^+$ and $^{190}Os^+$ is likely to be small because of its low concentration in most reagents and lower oxygen-atom affinity (93 kcal/mol).*

solutions, however, indicated that, not only does osmium react rapidly with oxygen in the cell, to produce both monoxide and dioxide ions, but that the dioxide ion is the dominant species, with approximately three-times the intensity of the atomic ion (*see* Table 26.1). Subsequent analyses of osmium were, therefore, performed by mass-shifting Os^+ to OsO_2^+ within the cell and measuring the intensity of the molecular ion.

Whereas osmium possesses 7 stable isotopes: ^{184}Os, ^{186}Os, ^{187}Os, ^{188}Os, ^{189}Os, ^{190}Os and ^{192}Os, only 4 isotopes (^{188}Os, ^{189}Os, ^{190}Os and ^{192}Os) are present at greater than 10% abundance (13.3, 16.1, 26.4 and 41%, respectively). Despite their higher abundances, when analyzed as their dioxide ions ($^{190}OsO_2^+$, m/z = 222; $^{192}OsO_2^+$, m/z = 224), ^{190}Os and ^{192}Os were found to suffer from isobaric polyatomic interferences when elevated concentrations of platinum or lead (Pb) are present in solution, creating $^{190}PtO_2^+$, $^{206}PbO^+$, $^{192}PtO_2^+$ or $^{208}PbO^+$ ions. Although less abundant, $^{189}OsO_2^+$ was found to experience no similar isobaric interferences (even from $^{205}TlO^+$, despite the presence of 40 ppb Tl as the internal standard) and was selected as the analyte used for the determination of osmium in solutions prepared for analysis by the IMP-200 method.

ACCURACY

The overall accuracy of osmium analysis by the IMP-200 method was estimated in 2 ways (Figure 26.5):

- from a weighted linear regression of the measured values against the reference values, weighted according to the uncertainties in the reference values (York 1966), giving a measure of overall bias in the measurement.
- from the average absolute deviation of the mean measured concentration relative to the reference value, giving a measure of the "average" accuracy (trueness) at concentrations greater than 3 times the blank-controlled limit of quantification (LoQ_{blank})[3].

Because very few reference materials are well characterized for osmium on their certificates of analysis, for many of the interlaboratory reference materials routinely analyzed by the IMP-200 method, the accuracy of the measured osmium contents was assessed against consensus values calculated from published values extracted from the GeoReM database (http://georem.mpch-mainz.gwdg.de; *see also* Jochum et al. 2005), using the median value as best estimate of the central value (Table 26.2).

Based on the average concentrations for procedural blanks and interlaboratory reference materials analyzed since August 2021 (*see* Table 26.2), osmium determined by the IMP-200 method shows blank-controlled limit of detection of around 0.053 ppb, an overall bias of −1.8% (*see* Figure 26.5A), and trueness of ±8.0% at greater than 0.16 ppb Os (3×LoQ, *see* Figure 26.5B).

PRECISION

The precision of osmium analysis by the IMP-200 method was estimated from duplicate analyses carried out on client samples during the validation period, using the method proposed by Thompson and Howarth (1976), with an additional component of uncertainty from the reference material analyses to account for long-term (between-batch or between-run) variations. For osmium determination by IMP-200, the estimated within-batch, within-run and within-sample variations recorded by the duplicate data for samples with moderate concentrations were able to account for most of the variation recorded by the reference materials routinely run for quality control. However, an additional uncertainty component appears to be necessary to account for longer term variations arising from short- and long-term between-run and/or between-batch variations (Figure 26.6).

[3] $LoQ_{blank} = mean_{blank} + 10 \times \sigma_{blank}$

When the additional component of the uncertainty is incorporated into the calculation of the precision-controlled limits of detection and quantification and the benchmark precision at elevated concentrations (typically 10×LoQ), they are higher than those suggested by blank analyses and approach 0.09 ppb Os, 0.3 ppb Os and ±15%, respectively.

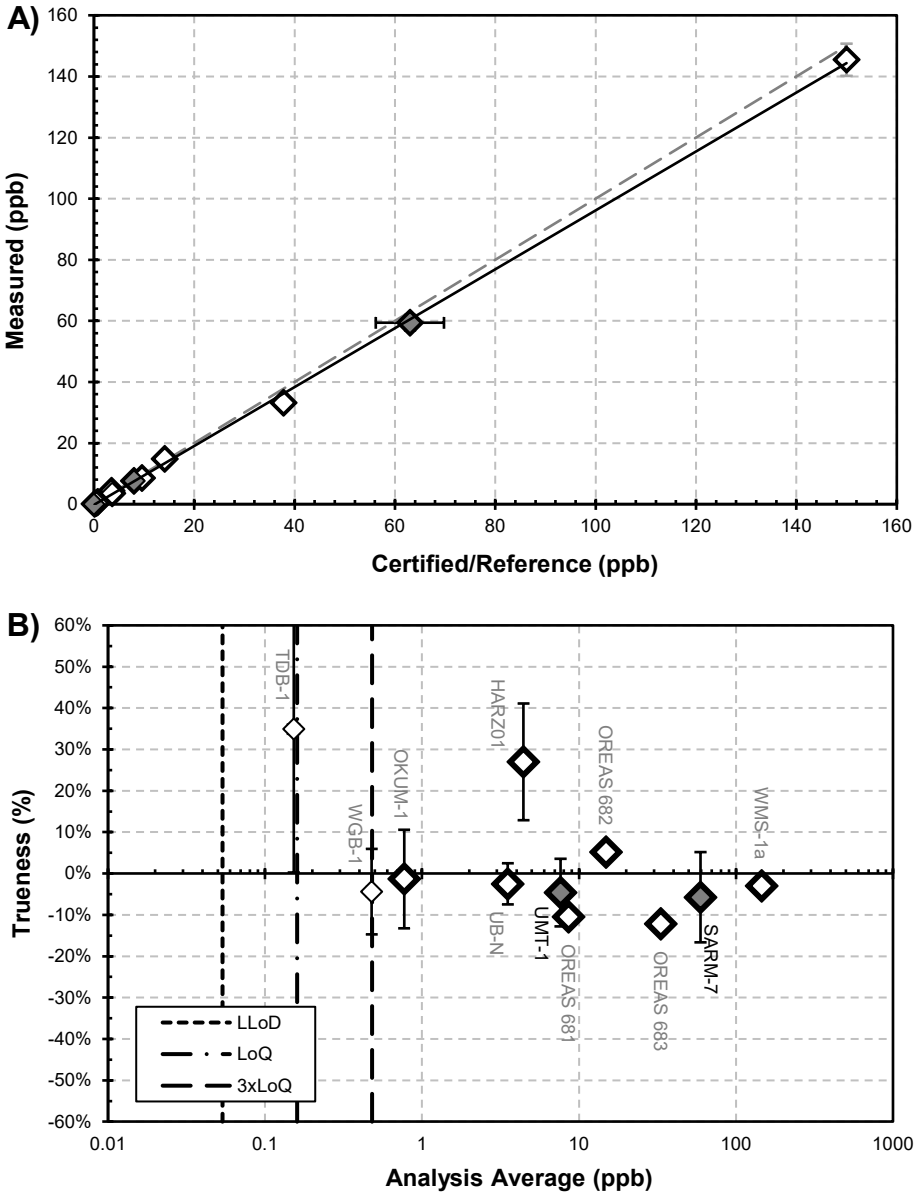


Figure 26.5. Comparison of measured and certified or reference values for osmium in interlaboratory reference materials analyzed by NiS fire assay (method code IMP-200). Grey symbols: certified values. Open symbols: reference or consensus values. Black outlines: materials with >3×LoQ used for the assessment of accuracy. **A**) Plot illustrating −1.8% bias (solid line) from weighted linear regression relative to 1:1 agreement (grey dashed line). **B**) Plot illustrating trueness (deviation of the average measured value and the certified or reference value) relative to limits of detection (LoD) and quantification (LoQ).

Table 26.2. Summary of osmium concentrations determined in reference materials August 2021 to September 2022.

Material	Certified/Reference Values (ppb)	Analysis Mean ±1σ (ppb)	n	$2S_r$
BLANK		0.008 ± 0.015	51	
HARZ01	3.49 ± 0.26 [a]	4.43 ± 0.36	11	8.2%
OKUM-1	0.780 ± 0.055 [a]	0.770 ± 0.075	6	9.8%
OREAS 681	9.58 [b]	8.58 ± 0.17	19	2.0%
OREAS 682	14.1 [b]	14.83 ± 0.64	14	4.3%
OREAS 683	37.8 [b]	33.2 ± 1.9	7	5.9%
SARM-7	63.0 ± 6.8 [c]	59.4 ± 2.5	10	4.2%
TDB-1	0.113 ± 0.012 [a]	0.152 ± 0.036	3	23.4%
UB-N	3.61 ± 0.12 [a]	3.52 ± 0.14	5	3.9%
UMT-1	8.0 ± 0.4 [a]	7.63 ± 0.53	6	6.9%
WGB-1	0.50 ± 0.03 [a]	0.478 ± 0.043	5	9.0%
WMS-1a	150 [d]	145.5 ± 5.3	12	3.6%

[a] *Median published value ± 1σ.*
[b] *Ore Research and Exploration (OREAS) certificate of analysis, information value.*
[c] *South African Bureau of Standards (SABS) certificate of analysis, certified value.*
[d] *Canadian Certified Reference Material Program (CCRMP) certificate of analysis, information value.*

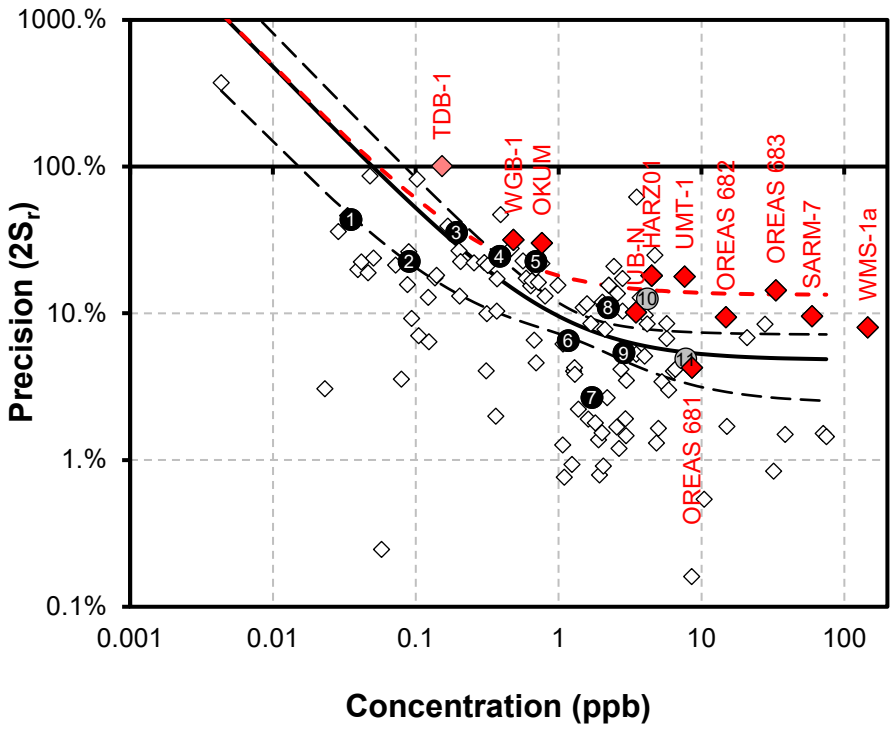


Figure 26.6. Relative precision ($2\sigma_r$) as a function of osmium concentration obtained using the IMP-200 method, estimated using the method proposed by Thompson and Howarth (1976). Small white diamonds: individual means of duplicate pairs. Large numbered circles: duplicate group means used in the regression. Red diamonds: quality-control material means used in calculations. Large pink diamonds: quality-control material means excluded from calculations (for TDB-1, only 3 analyses were performed). Black lines: uncertainty estimated from selected duplicate group means (black symbols only; dashed line = uncertainty on the regression). Red dashed line: overall uncertainty estimated including component for between-batch or between-run variations.

REPORTING LIMITS

A lower reporting limit of 0.09 ppb Os was conservatively set for the reporting of osmium by the IMP-200 method, based the precision-controlled limit of detection calculated from the reproducibility of duplicate analyses and the long-term variations in reference material analyses.

The upper reporting limit for osmium by the IMP-200 method (165 ppb) was set based on 110% of the highest reference material or proficiency test sample that was successfully analyzed (150 ppb in WMS-1a: *see* Table 26.2).

CONCLUSIONS

- Through the close matching of the matrices of osmium calibration solutions to those of samples prepared by NiS fire assay, it has been possible to produce sufficiently stable solutions for the determination of Os as part of the IMP-200 method.
- When using the stabilized calibration solutions, the IMP-200 method appears to be able to produce accurate osmium data over a wide range of concentrations, encompassing the majority of those seen in sample received by the Geo Labs.
- The precision of osmium analyses appears to be limited to ±15%, partly by between-batch and/or between-run variations and, as such, does not currently meet the Geo Labs quality criteria of better than ±10% precision at greater than 10×LoQ. Until this variation can be addressed, osmium data reported from the IMP-200 method should be considered as information values only.
- Further work will focus on identifying and eliminating the sources of variation with the aim of increasing the confidence in reported values

ACKNOWLEDGMENTS

The author would like to thank Troy Richardson for all the analytical work carried out during this project and Jen Hargreaves for her comments on the article.

REFERENCES

Bazan, J.M. 1987. Enhancement of osmium detection in inductively coupled plasma emission spectrometry; Analytical Chemistry, v.59, p.1066-1069.

Gregoire, D.C. 1990. Sample introduction techniques for the determination of osmium isotope ratios by inductively coupled plasma mass spectrometry; Analytical Chemistry, v.62, p.141-146.

Jochum, K.P., Nohl, W., Herwig, K., Lammell, E., Stoll, B. and Hofmann, A.W. 2005. GeoReM: A new geochemical database for reference materials and isotopic standards; Geostandards and Geoanalytical Research, v.29, p.333-338, doi.org/10.1111/j.1751-908X.2005.tb00904.x, online database available at http://georem.mpch-mainz.gwdg.de [accessed November 9, 2022]

Koyanagi, G.K. and Bohme, D.K. 2001. Ion-molecule reactions in plasma source mass spectrometry; *in* Plasma source mass spectrometry: The new millennium, The Royal Society of Chemistry, Cambridge, United Kingdom, p.117.

Richardson, J.M., Dickin, A.P., McNutt, R.H., McAndrew, J.I. and Beneteau, S.B. 1989. Analysis of a rhenium-osmium solid solution spike by inductively coupled plasma mass spectrometry; Journal of Analytical Atomic Spectrometry, v.4, p.465-471.

Richardson, T. and Burnham, O.M. 2002. Precious metal analysis at the Geoscience Laboratories: Results from the new low-level analytical facility; *in* Summary of Field Work and Other Activities, 2002, Ontario Geological Survey, Open File Report 6100, p.35-1 to 35-5.

Sugiyama, N. and Nakano, K. 2014. Reaction data for 70 elements using O_2, NH_3 and H_2 gases with the Agilent triple quadrupole ICP-MS; Agilent Technologies, Tokyo, Japan, Technical Note 5991-4585EN, p.1-14.

Thompson, M. and Howarth, R.J. 1976. Duplicate analysis in geochemical practice. Part 1: Theoretical approach and estimation of analytical reproducibility; The Analyst, v.101, p.690-698.

York, D. 1966. Least-squares fitting of a straight line; Canadian Journal of Physics, v.44, p.1079-1086.

27. Expansion of the Capabilities of the Geoscience Laboratories Methods for the Analysis of Trace Elements Important to Ontario's Critical Minerals Strategy



O.M. Burnham[1]

[1]Geoscience Laboratories, Ontario Geological Survey

INTRODUCTION

In March 2022, the Province of Ontario launched its first ever Critical Minerals Strategy, committing to identify, analyze and quantify critical minerals in new and historic deposits through enhanced geochemical analysis techniques. To support the Ontario Geological Survey's contribution to this strategy, the Geoscience Laboratories (Geo Labs) has embarked on a range of initiatives to expand its capabilities for the analysis of trace metals in mineralized and non-mineralized samples, including the following:

- developing alternative methods of analysis to overcome acid-resistance and/or volatility of minerals and elements during preparation or analysis
- expanding the capacity for precious metal analyses by fire-assay techniques
- increasing the upper reporting limits for elements targeted by the Critical Minerals Strategy and already part of one or more Geo Labs methods, and
- where missing, adding elements identified under the Critical Minerals Strategy to existing Geo Labs methods.

This article outlines some of the initiatives that are currently underway and progress to date.

ALTERNATIVE METHODS OF ANALYSIS

During geochemical analysis, it is rare that one method can deliver the best data in all circumstances, and it is often necessary to select the most appropriate method for a situation. Whereas the majority of the methods currently employed for the analysis trace elements at the Geo Labs are optimized for either the multi-element analysis of non-mineralized or weakly mineralized rocks collected during regional mapping projects (e.g., X-ray fluorescence (XRF) analysis on fused beads or pressed pellets or inductively coupled plasma mass spectrometric (ICP–MS) analysis of acid-digested samples) or the commodity-specific analysis of mineralized samples collected in support of exploration activities (e.g., flame-atomic absorbance spectrometric (F-AAS) analysis of base metals in acid-digested samples or gravimetric lead–fire assay analysis for gold), the focus of the Critical Minerals Strategy on alternative resources and the identification of critical mineral contents in tailings or waste rock has required the development of alternative methods of analysis for many trace elements in order to overcome problems

Summary of Field Work and Other Activities, 2022,
Ontario Geological Survey, Open File Report 6390, p.27-1 to 27-11.

© King's Printer for Ontario, 2022

that arise from the mineralized matrices and/or the presence of analytes in analytically challenging minerals. Typical challenges include the following:

- The presence of analytes in acid-resistant accessory phases that can be poorly recovered during routine open- or closed-beaker mixed-acid digestions. Because the mixed-acid digestions are optimized for the decomposition of silicate phases, because of their poorer solubility in hydrofluoric acid, many oxide (e.g., cassiterite, SnO_2; chromite, $FeCr_2O_4$; and possibly rutile, TiO_2) and some phosphate phases (e.g., monazite, $(Ce,La)PO_4$; and xenotime, YPO_4, commonly with high heavy rare-earth element (HREE) contents) can remain undigested, leading to low recoveries (Burnham et al. 2002).
- Volatility of analytes during acid attack. Like silicon, germanium, an element targeted by the Critical Minerals Strategy, forms a volatile tetrafluoride (GeF_4, $T_{sublim} = -36.5°C$) that is lost when solutions are dried down as part of routine hydrofluoric acid-based digestions. Therefore, to determine germanium, alternative, non-HF-based decomposition techniques were required.
- Non-linearity of calibrations. As concentrations increase, instrumental signal responses often become non-linear, and calibrations become considerably more complex. With the increased interest in multi-element analysis of mineralized samples, more robust versions of existing methods and/or alternative methods of analysis needed to be developed to extend the reporting range for many elements.
- Interferences arising from elevated concentrations in mineralized samples. Whereas spectral overlaps are routinely corrected during analysis during most analyses, when analyzing mineralized samples for trace components, not only can the magnitude of these interferences increase considerably, with an accompanying decrease in the accuracy of the corrections, but additional corrections can be required for interferences that have hitherto been minor and therefore overlooked.
- Solubility limits during acid digestions and/or fusions. As with any dissolution process, there can be a limit on the amount of an element that will either dissolve or remain in solution in an acid matrix (digestions) or borate liquid/glass (fusions). Such limits are independent of the mineral(s) hosting the element and can restrict the capacity of a method to determine the high concentrations that may be present in mineralized samples.

To overcome these challenges, the Geo Labs has undertaken the development of several alternative methods of sample preparation and analysis for mineralized samples, which supplement those currently used for routine materials. These include

- Lithium metaborate fusions combined with multi-element ICP–MS analysis for improved determination of tin, the rare earth elements (REE), tantalum and niobium in acid-resistant phases, and germanium in silicates and oxides. Although the blank levels in fusion reagents are commonly higher than in those used for acid digestions (increasing the detection limits for many analytes), metaborate fusions are better able to bring acid-resistant phases into solution, including the oxide and phosphate phases described above, and to retain elements that form volatile fluorides, such as germanium and silicon, allowing the characterization of both the major and trace element compositions of samples using the same solution, as well as more accurate analysis of samples with "difficult" mineralogies. The current initiative continues the work described by Burnham (2013), which focussed on the fusion of oxide-rich samples, and extends it to the routine analysis of silicate matrices. Work to date has focussed on the fusion recipe, in particular the choice of non-wetting agent used to ensure quantitative transfer of fused samples into acid for dissolution, and on methods of calibration. A validated method is expected to be in place in time for the analysis of samples collected during the 2023 field season.

- Energy-dispersive X-ray fluorescence (ED-XRF) spectrometry for the analysis of trace elements in pressed powder pellets, with an emphasis on the rare earth elements (REE) when present at elevated concentrations, and extension of the working ranges and/or interference tolerances of the current wavelength-dispersive trace element methods (method codes XRF-T02 to -T04). During 2020–2021, the Geo Labs replaced its Panalytical® Axios® wavelength dispersive X-ray fluorescence (WD-XRF) spectrometers with Panalytical® Zetium® instruments, in which an energy-dispersive core is combined with the previous wavelength-dispersive spectrometer system. The combination of WD-XRF and ED-XRF analysis in the same instrument opens up alternative approaches to analysis that may be applicable to Critical Minerals analysis:
    - Because no acid digestion is required and larger sample masses are analyzed (typically, X-ray signals should be obtained from masses of between 0.3 g and 1 g for the LREE and HREE, respectively), XRF analysis on pressed powder pellets avoids many of the issues associated with acid insolubility and/or sample heterogeneity of the REE (and other trace elements) when present in discrete accessory phases.
    - Because ED-XRF analyses can simultaneously acquire and deconvolute the complete X-ray spectrum across a wide range of energies, by combining ED-XRF with more conventional wavelength dispersive X-ray fluorescence (WD-XRF), the capacity for interference corrections is increased, without increasing analysis time. During WD-XRF analysis, for each analyte (reported elements as well as interferants), a peak and background intensity measurement is required. Such measurements are performed sequentially, so, the more interferences that need correction, the greater the analysis time. With the potentially greater complexity of the samples submitted during Critical Minerals studies, the range and magnitude of interferences that might need to be considered increases substantially. Whereas this would create a challenge for a pure WD-XRF instrument, by combining interference corrections calculated from ED-XRF analyses with analytes measurement on the WD-XRF system, an almost unlimited number of corrections can be applied without compromising sample throughput.

  Anticipated working ranges for the REE by ED-XRF are from 20 ppm to weight percent concentrations, lending it to the analysis of enriched rocks rather than refined products or concentrates. The improvements to matrix tolerance have yet to be quantified.

- High-dilution fusions for the preparation of fused beads for WD-XRF analysis. There are several advantages to reducing the sample:flux ratio used during the preparation of fused beads for major and minor element analysis by WD-XRF, especially when working with mineralized samples:
    - Increased analyte solubility: At the 1:8 sample:flux ratios routinely used for the preparation of fused beads at the Geo Labs, the analysis of chromium and the base metals (e.g., zinc, nickel, copper, lead and cobalt) is limited to around 3 weight % Cr_2O_3 or 3 weight % <u>total</u> base metal contents before the analytes fail to dissolve in the flux and/or start to form crystallites as the bead cools, both of which lead to inaccurate results (Burnham, Hechler and Chrétien 2010). If the sample:flux ratio is decreased to around 1:23 (0.35 g sample + 8 g flux), then the solubility of chromium increases, allowing samples with up to 15 weight % Cr_2O_3 to be fused. At a ratio of 1:40 (0.2 g sample + 8 g flux), it is higher still and allows for the preparation of samples with up to 50 weight % Cr_2O_3. By introducing one or more high-dilution fusion methods (with dilution factors of up to 1:40) and adapting the current XRF methods for the analysis of major and minor elements to accommodate high-dilution samples, it will be possible to expand the capacity of XRF analyses to include the quantification of the bulk compositions of chromitites, such as those from the “Ring of Fire” deposits, as well as base metal–rich tailings and/or historic mine samples studied as part of the Critical Minerals Strategy.

- Increased matrix tolerance: As the intensity of X-ray signals increase, so do the widths of the peaks, increasing overlaps and decreasing the accuracy of overlap corrections. Such corrections are critical during the analysis of several Critical Minerals, including vanadium in titanium-rich matrices (e.g., 2000–5000 ppm V in ilmenite or titanomagnetite deposits containing >20 weight % TiO_2, such as the Titan occurrence, northeastern Ontario: Easton 2002), Na_2O in zinc-, copper- or nickel-rich matrices (e.g., base metal–rich tailings and/or historic mine samples), or zirconium, strontium and titanium in barium-rich (barite-bearing) matrices. By increasing the dilution during fusion and decreasing the X-ray signals during analysis, it will be possible to maintain the accuracy of overlap corrections so that accurate major and minor element can be obtained despite mineralization.
- Decreased cross-contamination: During fusion, base metals, originally present as sulphides, but partially oxidized during the loss-on-ignition pre-treatment to remove sulphur, can auto-reduce to yield a higher oxide and metal that can alloy with the platinum-ware used for the fusion and thereby carryover into subsequent samples. This is most pronounced for copper, for which Cu_2O can be converted to copper oxide (CuO) and copper (Cu) metal, but can also occur to a decreasing degree for zinc, lead, nickel and cobalt. Increasing the dilution during fusion allows for better oxidation of the base metals, decreased alloying and less carryover between analyses. Such precautions will be necessary if base metal mineralized samples collected in support of the Critical Minerals Strategy are to be analyzed for their major element compositions without prejudicing routine production.

Much of the work to develop the necessary high-dilution fusions and accompanying instrumental methods for the analysis of mineralized samples is already complete and these methods have been used on a trial basis on selected samples submitted by clients for some time. Over the coming months, the methods will be finalized with the aim of having them available as routine analyses in time for the analysis of samples collected during the 2023 field season.

EXPANSION OF PRECIOUS METAL CAPACITY

Precious metals are currently analyzed by 4 different methods at the Geo Labs, depending on the metals of interest and their expected concentrations:

- lead fire-assay with a gravimetric finish (method code GFA-PBG) for the analysis of gold at concentrations greater than 0.016 ounces per ton (approximately 550 ppb Au)
- lead fire-assay with an ICP–MS finish (method code IMP-101) for the analysis of gold, platinum and palladium at concentrations greater than 0.05 to 0.6 ppb Au
- nickel sulphide fire-assay with an ICP–MS finish (method code IMP-200) for the analysis of gold, platinum, palladium, rhodium, ruthenium and iridium at concentrations between 0.007–0.3 ppb and 800–4200 ppb
- Modified *aqua regia* extraction with an ICP–MS finish (method code IML-101) for the analysis of gold, platinum, palladium and iridium at concentrations between 3–20 ppb and 80–100 ppm[2], along with pathfinder or fingerprinting elements for precious metal mineralization (e.g., antimony, arsenic, mercury, selenium and tellurium).

The 4 methods were created to accurately determine precious metal contents in samples ranging from non-mineralized primarily silicate matrices with low precious metal contents (e.g., IMP-101 and

[2] *Whereas the recoveries of gold and palladium are considered to be complete during the* aqua regia *extraction, platinum and iridium are only partially recovered, depending on their mineralogy. The upper reporting limits for these analytes is therefore considerably lower (2–3 ppm).*

IMP-200) to highly mineralized silicate and/or sulphide matrices with high precious metal contents, to match the range of samples received by the Geo Labs.

When necessary, the fusion recipes used for either the lead or nickel sulphide are customized for alternate matrices, but, to date, no standardized method has been established for the fusion of oxide-rich samples, in particular chromitites, which can host substantial concentrations of ruthenium, iridium and/or rhodium. In view of the heightened focus on chromitites as part of the Critical Minerals Strategy and the importance of ruthenium, iridium and/or rhodium concentrations to the characterization of such samples, the Geo Labs is working to establish a routine method for the analysis of chromite-rich samples using a fusion method modified after Bédard and Barnes (2004). This work will see the integration of the customized fusion method (using a sodium hexametaphosphate based flux) into the IMP-200 method, as well as the determination of the range of chromite contents for which each fusion method is most suitable.

INCREASED UPPER REPORTING LIMITS OF EXISTING METHODS

Base and Precious Metal Mineralization

Following increased interest in the broader characterization of base and precious metal mineralized samples and with the move to new instrumentation, in 2017, the Geo Labs expanded the range of analytes reported from modified *aqua regia* extractions with an ICP–MS finish (method code IML-101) from the primary base metals associated with magmatic sulphide and/or volcanogenic massive sulphide mineralization (i.e., cobalt, copper, lead, nickel, silver and zinc) to include a broad range of semi-metals and select precious metals that might be associated with or pathfinders for base and precious metal mineralization. Because many of these additional elements are included in the Critical Minerals Strategy, in 2021, an initiative was undertaken to determine whether the reporting range of these elements could be expanded, leading to the analysis of a suite of mineralized reference materials and the revision of the upper reporting limits for the Critical Minerals bismuth, cobalt, indium and palladium (Figure 27.1), as well as for arsenic, cadmium, mercury, silver and thallium (Table 27.1). Efforts to expand the upper reporting limit for tellurium were hampered by the paucity of well-characterized reference materials with elevated tellurium contents. Expansion of the upper limit for tellurium, therefore, is being approached through cross-method and/or interlaboratory validation (see below).

Fertile Granites and Lithium-Rich Pegmatites

The Geo Labs has several methods for the analysis of the Critical Minerals lithium, cesium, niobium, rubidium and tantalum, elements that can be strongly enriched in fertile granites and/or lithium-rich pegmatites. However, to date, only a few of these elements have been validated at the concentrations found in mineralized systems (Table 27.2). Therefore, during June 2022, a suite of lithium-rich reference materials was analyzed by the IMC-100 method (closed-beaker mixed-acid digestion followed by ICP–MS analysis). The results of these analyses show that the IMC-100 method is capable of producing accurate data at substantially higher concentrations than previously shown and concentrations that are close to those expected in economically significant samples, allowing the upper reporting limits to be increased for lithium, rubidium and cesium (Figure 27.2; *see* Table 27.2).

Having demonstrated successful sample digestion, future work will determine whether a similar increase in upper reporting limits can be achieved for analyses of similar solutions by inductively coupled plasma atomic emission spectrometry (ICP–AES), using either the current or a modified version of method code IAC-100. Given the high sensitivity of ICP–MS analysis and the difficulties associated with internal standard corrections at low atomic masses, ICP–AES may offer a better long-term solution for the analysis of lithium-rich materials and will be pursued when time and resources permit.

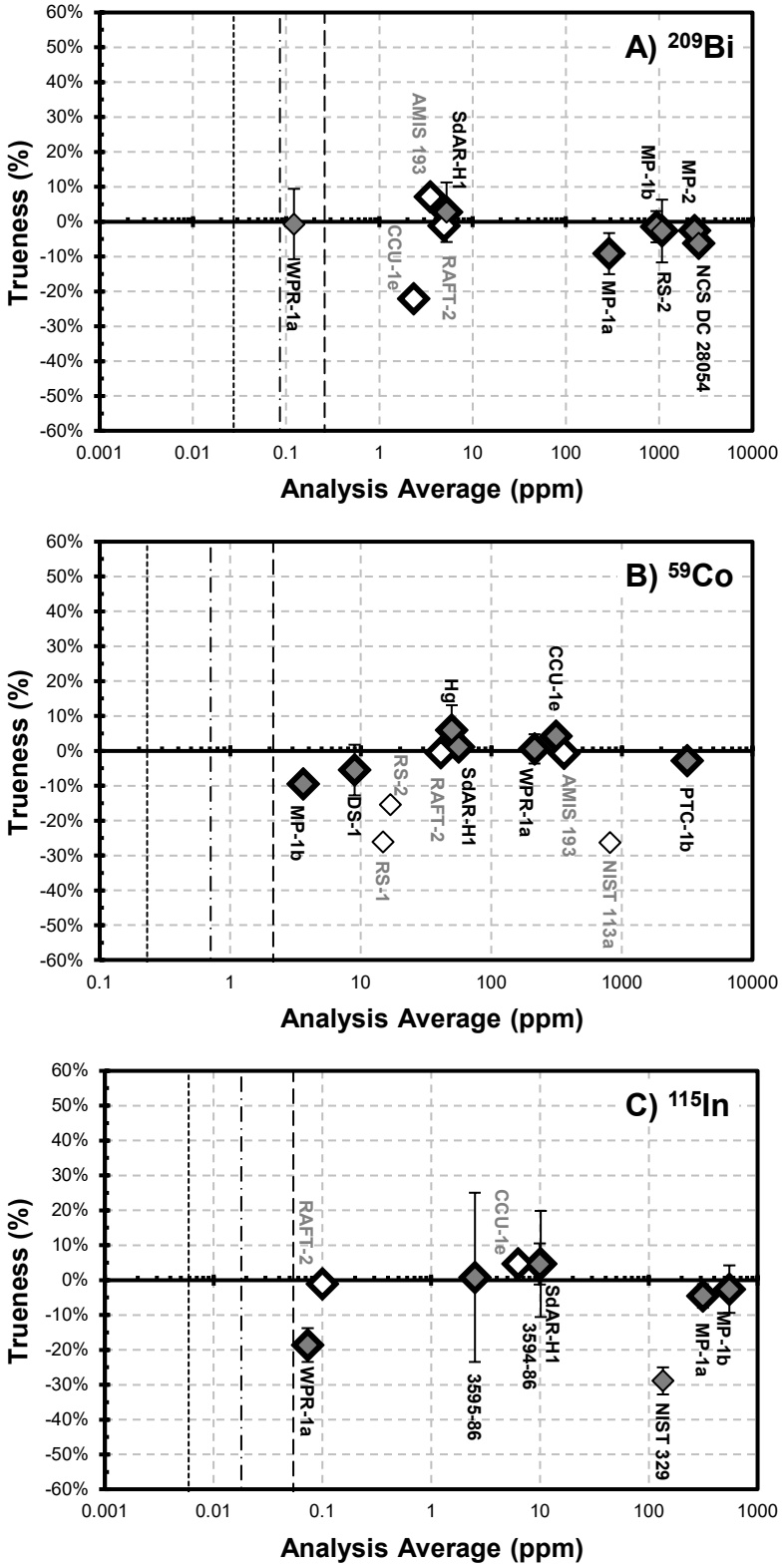


Figure 27.1. Trueness (deviation of the average measured value and the certified/reference value) of analyses of **A**) bismuth, **B**) cobalt and **C**) indium (analyzed at ^{209}Bi, ^{59}Co and ^{115}In) by ICP–MS after modified *aqua regia* extraction (method code IML-101). Grey symbols: certified values. Open symbols: reference or indicative values. Black outlines: materials with >3×LoQ (dashed line) used for the assessment of accuracy. Dotted line: limit of detection (LoD). Dot-dashed line: limit of quantification (LoQ).

Table 27.1. Summary of revised reporting limits for trace elements analyzed by Geo Labs method IML-101 (ICP–MS analysis mineralized rocks after a modified *aqua regia* extraction).

Analyte	Lower Limit (ppm)	Upper Limit (ppm)	
		2021	2022
Sb	**0.02**	**5500**	
As	4	7700	10000
Bi	**0.02**	**1200**	**3000**
Cd	0.05	50	8000
Co	**0.2**	**1000**	**3000**
Cu	**0.6**	**12000**	
Au	0.003	100	
In	**0.005**	**15**	**600**
Ir	**0.003**	**2**	
Pb	0.2	8000	
Hg	0.08	430	700
Mo	**0.2**	**17000**	
Ni	**2**	**22000**	
Pd	**0.02**	**5**	**80**
Pt	**0.005**	**3**	
Se	**0.2**	**90**	
Ag	0.2	80	150
Te	**0.04**	**40**	
Tl	0.004	11	40
Sn	**0.06**	**90**	
Zn	**4**	**30000**	

Bold: *Analytes on the Ontario Critical Minerals list.*

Table 27.2. Summary of reporting limits for Geo Labs methods used for the analysis of fertile granites and/or lithium-rich pegmatites relative to the reported compositions of selected Ontario deposits.

Method:	Bulk Analyses		IMC-100			XRF-T02/-T03		IAC-100		AAF-103	
Analyte	Big Whopper[a] (ppm)	PAK Lithium Project[b] (ppm)	LL (ppm)	UL (ppm)[c] 2022	UL (ppm)[c] 2023	LL (ppm)	UL (ppm)	LL (ppm)	UL (ppm)	LL (ppm)	UL (ppm)
Cs	15 – 146	236 – 490	0.018	700	1800	8	700				
Li	3200 – 11,000	1672 – 9245	0.24	5400	290,000			2	220	5	400
Nb	22 – 139	45 – 185	0.05	1900		0.8	1500				
Rb	2078 – 6908	1372 – 2835	0.15	4000	9400	0.6	3000				
Ta	14 – 204	161 – 232	0.015	320							
Sn	100 – 1300	101 – 694	0.17	140							

Abbreviations: *LL, lower limit; UL, upper limit.*
[a] *Bulk analysis from DDH 97-2 (Pedersen, Taylor and Campbell 2001).*
[b] *Drever (2016).*
[c] *110% of highest certified reference material successfully analyzed.*

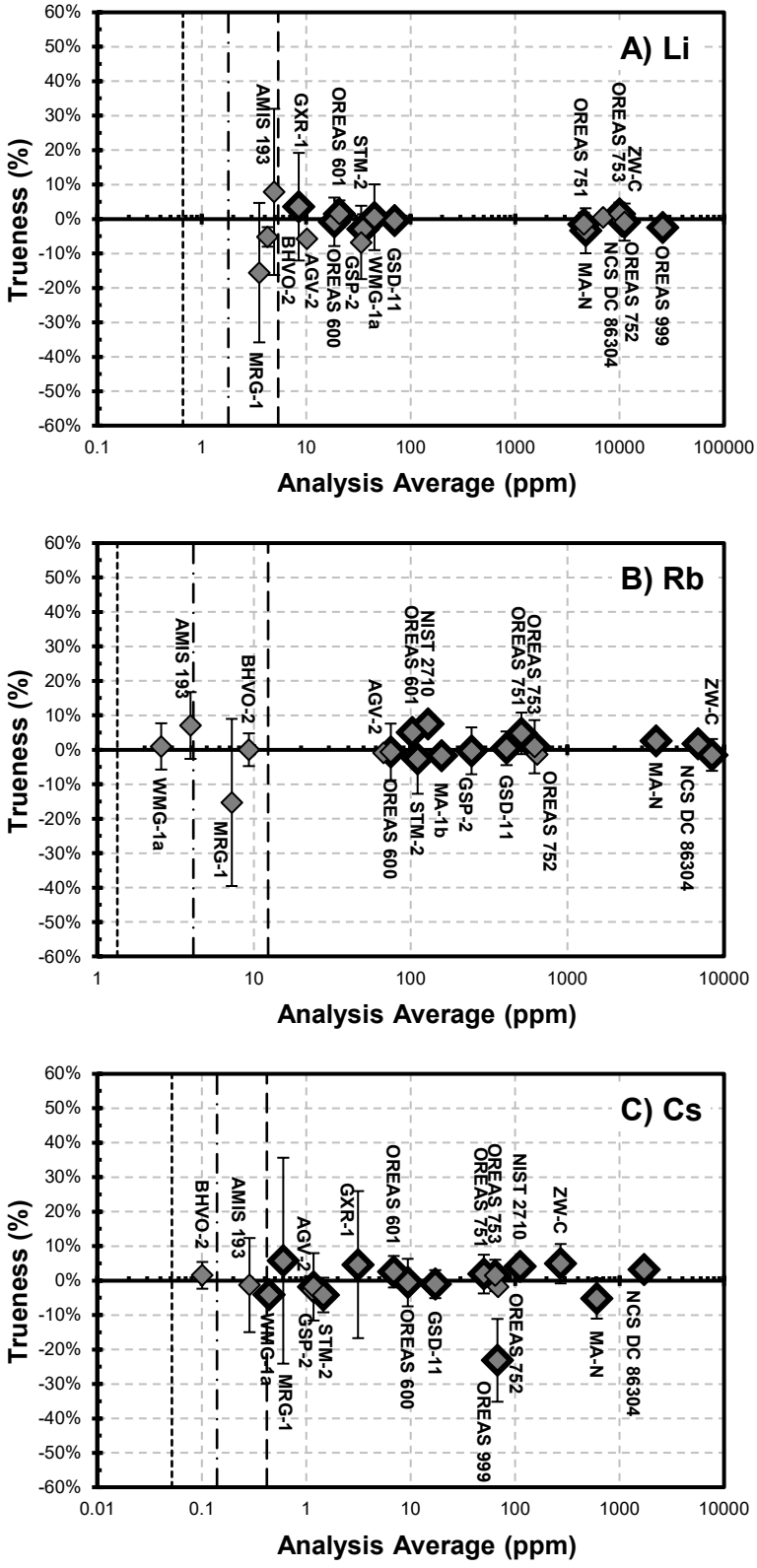


Figure 27.2. Trueness (deviation of the average measured value and the certified or reference value) of analyses of **A**) lithium, **B**) rubidium and **C**) cesium by ICP–MS after closed-beaker digestion (method code IMC-100). Grey symbols: certified values. Black outlines: materials with >3×LoQ (dashed line) used for the assessment of accuracy. Dotted line: limit of detection (LoD). Dot-dashed line: limit of quantification (LoQ).

ADDITION OF ANALYTES TO EXISTING METHODS

Almost all the trace elements listed in Ontario's Critical Minerals list are determined by at least one Geo Labs method and many are available from multiple methods. However, to cover the range of concentrations expected in mineralized samples, provide corroboration of data by an alternate method, and/or expand the range of analytes further, additional analytes will be introduced to some existing methods to support future analyses.

Tellurium

Currently, the only method from which tellurium is reported is IML-101 (ICP–MS analysis after modified *aqua regia* extraction), with a validated working range of 0.04 to 40 ppm. Although many gold and base metal deposits contain considerably higher tellurium concentrations than the upper reporting limit of the IML-101 method and such levels might need to be demonstrated for the extraction of the element to be considered economically feasible, increasing the validated range for tellurium analyses is obstructed by the absence of adequately characterized interlaboratory reference materials with elevated tellurium contents and appropriate matrices. The only interlaboratory reference materials that are currently available and certified to contain more than 60 ppm Te are pyrite concentrates that yield anomalously low results when analyzed using the IML-101 method. To overcome this obstacle, an initiative has been undertaken to a) expand the analytes reported from the IMC-100 method to include tellurium and b) characterize tellurium in selected tellurium-rich Mineral Research Branch (MRB) in-house quality-control materials (Richardson 1995) and mineralized samples collected as part of OGS-supported research, using data obtained within the Geo Labs and by analyses at external laboratories. An initial comparison of data obtained by Geo Labs methods IMC-100 and IML-101 indicates better than ±10% agreement for samples with a variety of matrices and concentrations up to 500 ppm Te (Figure 27.3), giving confidence in the values obtained by both methods, despite the poor performance for the pyrite concentrates. If external analyses of the same in-house quality-control materials and samples yield similar results, then the upper reporting limits for both methods could be extended to this level.

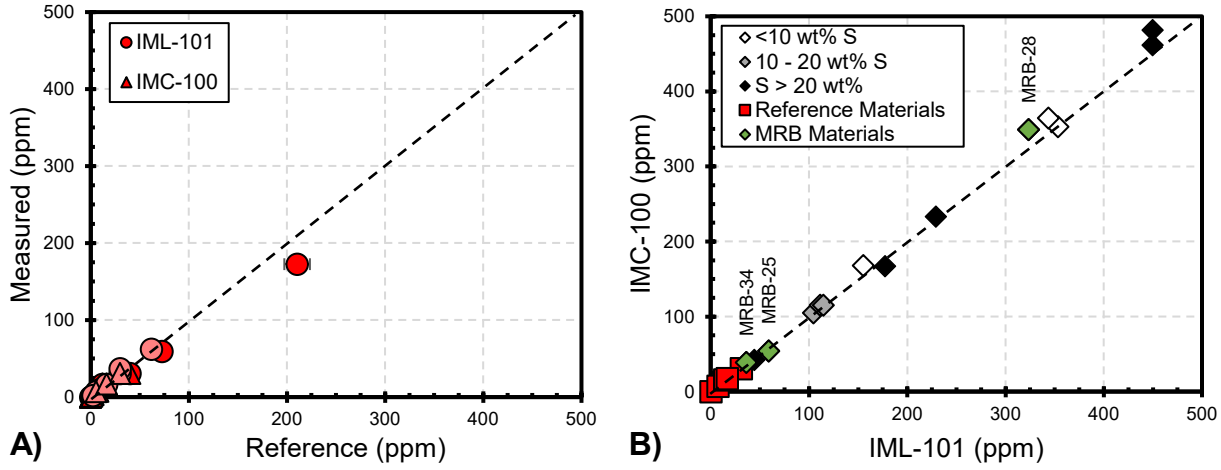


Figure 27.3. Comparisons of tellurium concentrations obtained by ICP–MS after *aqua regia* extraction and closed-beaker digestion (method codes IML-101 and IMC-100). **A**) Comparison of measured and certificate values for interlaboratory reference materials for concentrations obtained by the 2 Geo Labs methods. Red: certified values. Pink: indicative values. **B**) Comparison of concentrations obtained by the 2 Geo Labs methods in samples containing low, medium and high sulphide contents.

Osmium

Since it was originally established at the Geo Labs, the nickel sulphide fire assay method (method code IMP-200) has reported 5 of the 6 platinum group elements: ruthenium (Ru), rhodium (Rh), palladium (Pd), iridium (Ir) and platinum (Pt). The sixth platinum group element, osmium (Os), was not reported because of its problematic chemistry and difficulties in creating a stable matrix-matched calibration solution. Similar to iridium and ruthenium, osmium is concentrated into early formed cumulate rocks in ultramafic systems, in particular chromitites, and can both add value to a resource and yield information about its formation. In response to several client requests for the inclusion of osmium in the IMP-200 method, the analyte is being added to the method (*see* Burnham, this volume, Article 26). Initial results are very promising, with accurate data obtained for samples over a working range of around 0.1 to 150 ppb Os, but the precision obtained for many reference materials is below the Geo Labs target. Until this can be addressed, data are presented as information values only.

Fluorine

To support OGS work focussed on the exploration for and characterization of fluorspar deposits as part of the Critical Mineral Strategy, the Geo Labs is expanding the range of analytes determined by WD-XRF on pressed powder pellets using a fundamental parameters calibration (method code XRF-W01) to include fluorine, as well as sulphur. Because of the low atomic number of these analytes and complexity of the spectra brought about by the major elements present in the same wavelength range, a fundamental parameters model for calibration is needed to fully model the matrix. By taking a fundamental parameters approach, it should be possible to handle concentrations in excess of 50 weight % F, as well as to accommodate elevated sulphur contents. Therefore, this method should be able to extend the current capabilities of Geo Labs methods based on sodium carbonate fusions followed by ion-selective electrode analysis (method codes SOL-FDI and ISE-R01, upper working limit 11 weight % F) to include pure fluorspar (CaF_2: 48.7 weight % F), as well as sulphide-bearing precious metal–rich samples, where halogens may have played an important role in metallogenesis; however, because of reactions between base metal sulphides and the nickel crucibles used during the carbonate fusions, the ISE-R01 method cannot be used for samples containing anything more than trace levels of sulphide.

Work on a preliminary calibration for the method is complete and the calibration is now being refined. Based on silicate reference materials run to date, the method has been demonstrated to have a working range of at least 100 ppm to greater than 5 weight % F. Further work using synthetic standards will be used to increase the working range, with a target upper reporting limit of 50 weight % F.

Tin, Hafnium, Tantalum and Tungsten

As an alternative to solution analysis after either the routine closed-beaker mixed-acid digestion (method code IMC-100) or metaborate fusion currently being developed for the analysis of acid-resistant minerals (see above) and possibly to extend the range of concentrations that can be analyzed, methods for the analysis of tin, hafnium, tantalum and tungsten by WD-XRF on pressed powder pellets are being investigated with a view towards creating add-on submethods to the existing Geo Labs XRF-T02 or XRF-T03 methods. Because most OGS samples are already submitted for the XRF-T02 and XRF-T03 methods, pressed pellets will already be available so no additional sample preparation will be required and, as described above, because no digestion is required and larger sample masses are analyzed (excited masses are >1 g for hafnium, tantalum and tungsten in a typical granitic matrix), WD-XRF analysis on pressed powder pellets will also avoid some of the issues associated with acid solubility and/or sample heterogeneity during solution analysis of samples where trace elements are present in discrete accessory

phases. The sensitivity of the submethods is likely to be considerably poorer than that for the same analytes by the IMC-100 method, leading to reporting ranges of around 20 to 1000 ppm. In this respect, the method will lend itself to the analysis of enriched rocks rather than routine geochemical samples.

SUMMARY

Although the Geo Labs is capable of analyzing a comprehensive suite of elements in the types of samples that have historically been submitted to support OGS activities, it has several initiatives underway to enhance and expand its capacity for the analysis of mineralized samples that might be submitted in support of Ontario's Critical Minerals Strategy. These initiatives include the development of new methods and/or the modification of existing methods to handle different sample types, the addition of analytes to routine methods, and the duplication of analytes between methods as a monitor for data accuracy. These will be worked on over the coming months and reported on in future articles.

ACKNOWLEDGMENTS

I would like to acknowledge the help of Glenna Keating, Michelle Moore and Troy Richardson in putting together this article and for providing preliminary data for plots.

REFERENCES

Bédard, L.P. and Barnes, S-J. 2004. Improved platinum-group element extraction by NiS fire assay from chromitite ore samples using a flux containing sodium metaphosphate; Geostandards and Geoanalytical Research, v.28, p.311-316.

Burnham, O.M. 2013. Analysis of oxide-rich samples by inductively coupled plasma mass spectrometry following lithium metaborate fusion; *in* Summary of Field Work and Other Activities, 2013, Ontario Geological Survey, Open File Report 6290, p.44-1 to 44-14.

Burnham, O.M., Hechler, J.H. and Chrétien, N. 2010. Improvements to the analysis of chromite-rich samples by X-ray fluorescence spectrometry at the Geoscience Laboratories: Effect of sample:flux ratios during fused disk preparation; *in* Summary of Field Work and Other Activities, 2010, Ontario Geological Survey, Open File Report 6260, p.41-1 to 41-6.

Burnham, O.M., Hechler, J., Semenyna, L. and Schweyer, J. 2002. Mineralogical controls on the determination of trace elements following mixed acid dissolution; *in* Summary of Field Work and Other Activities, 2002, Ontario Geological Survey, Open File Report 6100, p.36-1 to 36-12.

Drever, G.L. 2016. 2015 Exploration on the PAK lithium project, northwestern Ontario, Houston Lake Mining Inc.; unpublished report, Red Lake Resident Geologist's office, assessment file AFRO# 2.56966 AFRI# 20000014116, 988p.

Easton, R.M. 2002. Geology of mafic intrusions of Flett and Angus townships, Grenville Province; Ontario Geological Survey, Open File Report 6090, 70p.

Pederson, J.C., Taylor, R.P. and Campbell, I.J. 2001. The Big Whopper petalite deposits, A major new rare metal pegmatite, Separation Rapids, northwestern Ontario; *in* Industrial minerals in Canada, Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume 53, p.179-186.

Richardson, J.M. 1995. 1995 update report on the composition of the Geoscience Laboratories in-house reference materials (MRB series); *in* Summary of Field Work and Other Activities, 1995, Ontario Geological Survey, Miscellaneous Paper 164 p.198–203.

28. Summary of Quality Control Data for the Geoscience Laboratories Methods IMC-100, IMO-100 and IMP-101



J.C. Hargreaves[1]

[1]Geoscience Laboratories, Ontario Geological Survey

INTRODUCTION

This article summarizes the results of analyses for quality-control samples for the Geoscience Laboratories methods IMC-100, IMO-100 and IMP-101. The IMC-100 test code is the determination of minor and trace elements by a closed-vessel multi-acid digestion followed by inductively coupled plasma mass spectrometry (ICP–MS). The IMO-100 test code is the determination of minor and trace elements by an open-vessel multi-acid digestion followed by inductively coupled plasma mass spectrometry (ICP–MS). The IMP-101 test code represents the determination of gold, palladium and platinum by lead–fire assay followed by inductively coupled plasma mass spectrometry (ICP–MS).

The quality-control data for the IMC-100 and IMO-100 test methods are summarized from September 13, 2017, to July 7, 2022, to capture results obtained since a summary was last published (Hargreaves 2017). The quality-control data for the IMP-101 test method are summarized from October 1, 2018, to July 7, 2022, to capture results obtained since the method was transferred to new ICP–MS instrumentation.

ACKNOWLEDGMENTS

The author would like to thank Marcus Burnham, Brent Handford, Victoria Hingst and Michelle Moore for their help in preparing this article.

REFERENCES

Hargreaves, J.C. 2017. Summary of quality control data for the Geoscience Laboratories methods EMP-100, IMC-100, IMO-100 and ISE-R01; *in* Summary of Field Work and Other Activities, 2017, Ontario Geological Survey, Open File Report 6333, p.32-1 to 32-15.

Summary of Field Work and Other Activities, 2022,
Ontario Geological Survey, Open File Report 6390, p.12-1 to 12-12.

© King's Printer for Ontario, 2022

Table 28.1. Summary of results obtained by the IMC-100 test method for in-house and certified reference materials from September 13, 2017, to July 7, 2022.

Material	Provider	Description	Ba (ppm)	Be (ppm)	Bi (ppm)	Cd (ppm)	Ce (ppm)	Co (ppm)
In-house Reference Materials								
LK-NIP-1	In-house	Diabase Sill	139.3 ± 1.5 (18)	0.54 ± 0.06 (18)	<0.11	0.118 ± 0.010 (18)	18.8 ± 0.6 (18)	58.0 ± 1.4 (18)
MRB-29	In-house	Basalt	287 ± 8 (943)	0.98 ± 0.07 (943)	<0.11	0.12 ± 0.29 (944)	48.2 ± 1.3 (943)	51.2 ± 2.7 (943)
ODL-1	In-house	Dolomitic Limestone	57.0 ± 1.4 (118)	0.51 ± 0.04 (118)	<0.11	0.143 ± 0.014 (118)	29.5 ± 0.8 (118)	9.3 ± 0.3 (118)
QS-1	In-house	Calcareous Shale	352 ± 16 (5)	2.27 ± 0.10 (5)	0.223 ± 0.011 (5)	0.076 ± 0.009 (5)	79.2 ± 1.8 (5)	16.2 ± 0.4 (5)
RV-1	In-house	Melagabbro	216.9 ± 1.4 (5)	0.45 ± 0.04 (5)	0.48 ± 0.04 (5)	0.305 ± 0.030 (5)	7.28 ± 0.16 (5)	73.9 ± 2.4 (5)
Certified Reference Materials								
AGV-2	USGS	Andesite	1,121 ± 39 (373)	2.05 ± 0.12 (373)	<0.11	0.077 ± 0.013 (373)	67.2 ± 2.9 (373)	16.0 ± 0.8 (373)
*Certificate*ǂ			*1140 ± 32*	*2.3 ± 0.4*	*NA*	*NA*	*68 ± 3*	*16 ± 1*
BHVO-2	USGS	Basalt	131 ± 4 (294)	1.00 ± 0.07 (294)	<0.11	0.102 ± 0.012 (294)	37.1 ± 1.0 (294)	45.7 ± 2.3 (294)
*Certificate*ǂ			*130 ± 13*	*NA*	*NA*	*NA*	*38 ± 2*	*45 ± 3*
GSP-2	USGS	Granodiorite	1,341 ± 45 (279)	1.38 ± 0.09 (279)	<0.11	0.100 ± 0.020 (279)	436 ± 12 (279)	7.3 ± 0.4 (279)
*Certificate*ǂ			*1340 ± 44*	*1.5 ± 0.2**	*NA*	*NA*	*410 ± 30*	*7.3 ± 0.8*
GSR-6	IGGE	Limestone	125 ± 4 (111)	0.72 ± 0.06 (111)	0.147 ± 0.021 (111)	0.063 ± 0.009 (111)	25.8 ± 0.6 (111)	9.3 ± 0.6 (111)
Certificate†			*120 ± 12*	*0.8 ± 0.2*	*0.16 ± 0.04*	*0.07 ± 0.02*	*25 ± 3*	*9 ± 2*
OKUM-1	IAG	Ultramafic Komatiite	5.7 ± 0.6 (52)	0.064 ± 0.012 (52)	<0.11	0.050 ± 0.006 (52)	1.25 ± 0.06 (52)	89 ± 5 (52)
Certificate‡			*6.2 ± 0.5**	*0.065 ± 0.004**	*NA*	*NA*	*1.27 ± 0.03*	*88.9 ± 1.5*
SU-1b	CANMET	Ni-Cu-Co Ore	147 ± 14 (3) [a]	0.467 ± 0.030 (3)	2.32 ± 0.28 (3)	3.10 ± 0.09 (3)	35.2 ± 2.2 (3)	626 ± 33 (3)
Certificate‡			*350**	*0.4**	*2.73***	*3**	*35**	*672 ± 13*
SY-4	CANMET	Diorite Gneiss	345 ± 7 (4)	2.64 ± 0.26 (4)	<0.11	0.105 ± 0.022 (4)	120.9 ± 2.6 (4)	2.66 ± 0.26 (4)
Certificate‡			*340 ± 5*	*2.6 ± 0.1*	*0.1-0.3**	*NA*	*122 ± 2*	*2.8 ± 0.2*

Notes: *Compiled data given as mean ± 1 standard deviation of results (number of measurements).*
ǂ *= Certificate value is average ± 1 standard deviation of the laboratory means.*
† *= Certificate value is average ± 99% confidence interval on the population mean.*
‡ *= Certificate value is average ± 95% confidence interval on the population mean.*
Abbreviations: *CANMET = Canada Centre for Mineral and Energy Technology; IAG = International Association of Geoanalysts; IGGE = Institute of Geophysical and Geochemical Exploration, China; USGS = United States Geological Survey.*
NA = not available.
**Information values.*
***Provisional values.*
[a] *Measured Ba contents of SU-1b low because of oxidation of sulphide to sulphate during digestion and precipitation of insoluble* $BaSO_4$.

Table 28.1, ***continued.***

Material	Provider	Description	Cr (ppm)	Cs (ppm)	Cu (ppm)	Dy (ppm)	Er (ppm)	Eu (ppm)
In-house Reference Materials								
LK-NIP-1	In-house	Diabase Sill	162 ± 5 (18)	0.584 ± 0.011 (18)	172 ± 6 (18)	4.06 ± 0.08 (18)	2.40 ± 0.07 (18)	1.099 ± 0.031 (18)
MRB-29	In-house	Basalt	282 ± 13 (943)	0.241 ± 0.009 (943)	148 ± 14 (943)	5.26 ± 0.18 (943)	2.82 ± 0.11 (943)	1.90 ± 0.07 (943)
ODL-1	In-house	Dolomitic Limestone	14.4 ± 0.8 (118)	1.14 ± 0.03 (118)	38.2 ± 1.9 (118)	2.26 ± 0.09 (118)	1.09 ± 0.04 (118)	0.668 ± 0.027 (118)
QS-1	In-house	Calcareous Shale	73.6 ± 1.6 (5)	6.24 ± 0.10 (5)	10.20 ± 0.22 (5)	5.30 ± 0.19 (5)	2.96 ± 0.14 (5)	1.417 ± 0.030 (5)
RV-1	In-house	Melagabbro	242 ± 9 (5)	0.515 ± 0.006 (5)	1,937 ± 124 (5)	0.973 ± 0.023 (5)	0.646 ± 0.019 (5)	0.399 ± 0.010 (5)
Certified Reference Materials								
AGV-2	USGS	Andesite	16.5 ± 1.0 (373)	1.15 ± 0.03 (373)	50.5 ± 2.4 (373)	3.47 ± 0.14 (373)	1.83 ± 0.08 (373)	1.52 ± 0.07 (373)
Certificateǂ			*17 ± 2*	*1.16 ± 0.08**	*53 ± 4*	*3.6 ± 0.2*	*1.79 ± 0.11**	*1.54 ± 0.10*
BHVO-2	USGS	Basalt	300 ± 12 (294)	0.099 ± 0.005 (294)	128 ± 6 (294)	5.37 ± 0.20 (294)	2.60 ± 0.11 (294)	2.10 ± 0.08 (294)
Certificateǂ			*280 ± 19*	*NA*	*127 ± 7*	*NA*	*NA*	*NA*
GSP-2	USGS	Granodiorite	20.7 ± 1.0 (279)	1.17 ± 0.03 (279)	43.9 ± 2.2 (279)	5.80 ± 0.22 (279)	2.35 ± 0.10 (279)	2.28 ± 0.09 (279)
Certificateǂ			*20 ± 6*	*1.2 ± 0.1**	*43 ± 4*	*6.1**	*2.2**	*2.3 ± 0.1*
GSR-6	IGGE	Limestone	33 ± 25 (111)	2.71 ± 0.08 (111)	22.1 ± 2.5 (111)	1.63 ± 0.06 (111)	0.911 ± 0.030 (111)	0.479 ± 0.016 (111)
Certificate†			*32 ± 6*	*3.2 ± 0.7*	*23 ± 2*	*1.6 ± 0.2*	*1.0 ± 0.2*	*0.51 ± 0.05*
OKUM-1	IAG	Ultramafic Komatiite	2,529 ± 102 (52)	0.177 ± 0.006 (52)	43.2 ± 1.4 (52)	1.55 ± 0.05 (52)	1.03 ± 0.04 (52)	0.296 ± 0.012 (52)
Certificate‡			*2,460 ± 31*	*0.184 ± 0.003*	*43.5 ± 1.2*	*1.61 ± 0.04*	*1.041 ± 0.014*	*0.300 ± 0.007*
SU-1b	CANMET	Ni-Cu-Co Ore	345 ± 8 (3)	0.256 ± 0.005 (3)	11,051 ± 197 (3)	1.48 ± 0.05 (3)	0.72 ± 0.07 (3)	0.79 ± 0.04 (3)
Certificate‡			*320**	*0.3**	*11,850 ± 140*	*1.4**	*0.7**	*0.7**
SY-4	CANMET	Diorite Gneiss	8.96 ± 0.09 (4)	1.581 ± 0.017 (4)	4.1 ± 0.9 (4)	19.1 ± 0.6 (4)	14.7 ± 0.4 (4)	1.96 ± 0.06 (4)
Certificate‡			*12 ± 1*	*1.5 ± 0.1*	*7 ± 1*	*18.2 ± 0.6*	*14.2 ± 0.5*	*2.00 ± 0.04*

Notes: *Compiled data given as mean ± 1 standard deviation of results (number of measurements).*
ǂ = Certificate value is average ± 1 standard deviation of the laboratory means.
† = Certificate value is average ± 99% confidence interval on the population mean.
‡ = Certificate value is average ± 95% confidence interval on the population mean.
Abbreviations: *CANMET = Canada Centre for Mineral and Energy Technology; IAG = International Association of Geoanalysts; IGGE = Institute of Geophysical and Geochemical Exploration, China; USGS = United States Geological Survey.*
NA = not available.
**Information values.*
***Provisional values.*

Table 28.1, ***continued.***

Material	Provider	Description	Ga (ppm)	Gd (ppm)	Hf (ppm)	Ho (ppm)	In (ppm)	La (ppm)
In-house Reference Materials								
LK-NIP-1	In-house	Diabase Sill	19.3 ± 0.4 (18)	3.77 ± 0.09 (18)	2.31 ± 0.06 (18)	0.834 ± 0.020 (18)	0.0658 ± 0.0021 (18)	8.48 ± 0.15 (18)
MRB-29	In-house	Basalt	19.5 ± 0.5 (943)	6.00 ± 0.22 (943)	4.44 ± 0.14 (943)	1.02 ± 0.04 (943)	0.0770 ± 0.0030 (943)	21.5 ± 0.6 (943)
ODL-1	In-house	Dolomitic Limestone	2.91 ± 0.08 (118)	2.87 ± 0.10 (118)	0.73 ± 0.06 (118)	0.418 ± 0.018 (118)	0.0198 ± 0.0011 (118)	15.5 ± 0.4 (118)
QS-1	In-house	Calcareous Shale	19.7 ± 0.4 (5)	5.88 ± 0.12 (5)	4.00 ± 0.12 (5)	1.04 ± 0.06 (5)	0.0679 ± 0.0025 (5)	38.1 ± 1.0 (5)
RV-1	In-house	Melagabbro	15.3 ± 0.3 (5)	0.856 ± 0.025 (5)	0.52 ± 0.05 (5)	0.208 ± 0.009 (5)	0.0378 ± 0.0007 (5)	3.62 ± 0.04 (5)
Certified Reference Materials								
AGV-2	USGS	Andesite	20.4 ± 0.5 (373)	4.49 ± 0.19 (373)	5.17 ± 0.30 (373)	0.662 ± 0.029 (373)	0.0442 ± 0.0019 (373)	37.0 ± 1.5 (373)
*Certificate*ǂ			*20 ± 1*	*4.69 ± 0.26***	*5.08 ± 0.20**	*0.71 ± 0.08**	*NA*	*38 ± 1*
BHVO-2	USGS	Basalt	21.3 ± 0.6 (294)	6.32 ± 0.23 (294)	4.45 ± 0.15 (294)	0.99 ± 0.04 (373)	0.086 ± 0.003 (294)	15.2 ± 0.4 (294)
*Certificate*ǂ			*21.7 ± 0.9*	*6.3 ± 0.2**	*4.1 ± 0.3*	*1.04 ± 0.04**	*NA*	*15 ± 1*
GSP-2	USGS	Granodiorite	22.3 ± 0.7 (279)	12.1 ± 0.5 (279)	12.9 ± 0.8 (279)	0.96 ± 0.04 (373)	0.0499 ± 0.0025 (279)	183 ± 5 (279)
*Certificate*ǂ			*22 ± 2*	*12 ± 2**	*14 ± 1*	*1.0 ± 0.1**	*NA*	*180 ± 12*
GSR-6	IGGE	Limestone	6.85 ± 0.18 (111)	1.86 ± 0.07 (111)	1.57 ± 0.06 (111)	0.321 ± 0.012 (373)	0.0264 ± 0.0012 (111)	12.9 ± 0.3 (111)
Certificate†			*7.1 ± 0.8*	*1.9 ± 0.2*	*1.8 ± 0.3*	*0.33 ± 0.05*	*0.04**	*15 ± 4*
OKUM-1	IAG	Ultramafic Komatiite	9.02 ± 0.21 (52)	1.16 ± 0.05 (52)	0.565 ± 0.024 (52)	0.341 ± 0.011 (373)	0.0339 ± 0.0020 (52)	0.403 ± 0.020 (52)
Certificate‡			*8.79 ± 0.16*	*1.17 ± 0.07**	*0.551 ± 0.023*	*0.355 ± 0.009*	*NA*	*0.412 ± 0.017*
SU-1b	CANMET	Ni-Cu-Co Ore	11.54 ± 0.08 (3)	2.28 ± 0.03 (3)	2.08 ± 0.15 (3)	0.274 ± 0.016 (373)	0.485 ± 0.020 (3)	16.7 ± 1.1 (3)
Certificate‡			*10**	*2**	*NA*	*0.3**	*NA*	*17**
SY-4	CANMET	Diorite Gneiss	35.44 ± 0.29 (4)	14.3 ± 0.5 (4)	8.8 ± 0.6 (4)	4.47 ± 0.11 (373)	0.0392 ± 0.0015 (4)	57.2 ± 1.6 (4)
Certificate‡			*35 ± 1*	*14.0 ± 0.5*	*10.6 ± 0.4*	*4.3 ± 0.1*	*0.04 - 0.1*	*58 ± 1*

Notes: *Compiled data given as mean ± 1 standard deviation of results (number of measurements).*
ǂ *= Certificate value is average ± 1 standard deviation of the laboratory means.*
† *= Certificate value is average ± 99% confidence interval on the population mean.*
‡ *= Certificate value is average ± 95% confidence interval on the population mean.*
Abbreviations: *CANMET = Canada Centre for Mineral and Energy Technology; IAG = International Association of Geoanalysts; IGGE = Institute of Geophysical and Geochemical Exploration, China; USGS = United States Geological Survey.*
NA = not available.
**Information values.*
***Provisional values.*

Table 28.1, ***continued.***

Material	Provider	Description	Li (ppm)	Lu (ppm)	Mo (ppm)	Nb (ppm)	Nd (ppm)	Ni (ppm)
In-house Reference Materials								
LK-NIP-1	In-house	Diabase Sill	9.8 ± 0.4 (18)	0.325 ± 0.011 (18)	1.07 ± 0.09 (18)	4.47 ± 0.07 (18)	11.60 ± 0.22 (18)	149 ± 4 (18)
MRB-29	In-house	Basalt	10.2 ± 0.7 (943)	0.356 ± 0.016 (943)	0.76 ± 0.07 (943)	12.5 ± 0.5 (943)	27.8 ± 0.8 (943)	111 ± 5 (943)
ODL-1	In-house	Dolomitic Limestone	11.6 ± 1.1 (118)	0.118 ± 0.005 (118)	0.99 ± 0.07 (118)	2.20 ± 0.08 (118)	15.5 ± 0.4 (118)	10.9 ± 1.9 (118)
QS-1	In-house	Calcareous Shale	57.6 ± 2.3 (5)	0.399 ± 0.022 (5)	1.15 ± 0.05 (5)	13.85 ± 0.25 (5)	36.7 ± 0.8 (5)	38.0 ± 1.3 (5)
RV-1	In-house	Melagabbro	19.8 ± 0.6 (5)	0.103 ± 0.003 (5)	0.89 ± 0.19 (5)	0.647 ± 0.019 (5)	3.69 ± 0.04 (5)	578 ± 12 (5)
Certified Reference Materials								
AGV-2	USGS	Andesite	9.9 ± 0.6 (373)	0.246 ± 0.013 (373)	1.98 ± 0.17 (373)	13.1 ± 0.7 (373)	30.3 ± 1.2 (373)	18.6 ± 1.1 (373)
*Certificate*ǂ			*11**	*0.25 ± 0.01**	*NA*	*15 ± 1*	*30 ± 2*	*19 ± 3*
BHVO-2	USGS	Basalt	4.22 ± 0.27 (294)	0.281 ± 0.014 (294)	4.2 ± 0.7 (294)	17.2 ± 0.5 (294)	24.8 ± 0.7 (294)	121 ± 5 (294)
*Certificate*ǂ			*5**	*0.28 ± 0.01**	*NA*	*18 ± 2**	*25.0 ± 1.8*	*119 ± 7*
GSP-2	USGS	Granodiorite	34.2 ± 2.1 (279)	0.227 ± 0.012 (279)	2.14 ± 0.18 (279)	25.2 ± 0.7 (279)	207 ± 6 (279)	16.3 ± 0.9 (279)
*Certificate*ǂ			*36 ± 1**	*0.23 ± 0.03**	*2.1 ± 0.6**	*27 ± 2*	*200 ± 12*	*17 ± 2*
GSR-6	IGGE	Limestone	20.5 ± 1.8 (111)	0.125 ± 0.005 (111)	0.5 ± 0.6 (111)	5.89 ± 0.21 (111)	11.67 ± 0.30 (111)	21 ± 13 (111)
Certificate†			*20 ± 3*	*0.14 ± 0.03*	*0.38 ± 0.06*	*6.6 ± 1.7*	*12.0 ± 1.0*	*18 ± 2*
OKUM-1	IAG	Ultramafic Komatiite	3.9 ± 0.7 (52)	0.147 ± 0.007 (52)	0.24 ± 0.05 (52)	0.339 ± 0.013 (52)	1.49 ± 0.06 (52)	895 ± 39 (52)
Certificate‡			*4.4 ± 0.3*	*0.148 ± 0.005*	*NA*	*0.37 ± 0.06*	*1.494 ± 0.020*	*886 ± 10*
SU-1b	CANMET	Ni-Cu-Co Ore	8.5 ± 0.5 (3)	0.093 ± 0.007 (3)	3.86 ± 0.12 (3)	2.97 ± 0.05 (3)	17.3 ± 1.2 (3)	18,347 ± 187 (3)
Certificate‡			*NA*	*NA*	*NA*	*NA*	*NA*	*19,530 ± 170*
SY-4	CANMET	Diorite Gneiss	31.9 ± 3.0 (4)	2.11 ± 0.05 (4)	0.226 ± 0.019 (4)	13.55 ± 0.15 (4)	59.0 ± 1.6 (4)	7.3 ± 0.3 (4)
Certificate‡			*37 ± 2*	*2.1 ± 0.1*	*0.2 – 3**	*13 ± 1*	*57 ± 1*	*9 ± 1*

Notes: *Compiled data given as mean ± 1 standard deviation of results (number of measurements).*
ǂ *= Certificate value is average ± 1 standard deviation of the laboratory means.*
† *= Certificate value is average ± 99% confidence interval on the population mean.*
‡ *= Certificate value is average ± 95% confidence interval on the population mean.*
Abbreviations: *CANMET = Canada Centre for Mineral and Energy Technology; IAG = International Association of Geoanalysts; IGGE = Institute of Geophysical and Geochemical Exploration, China; USGS = United States Geological Survey.*
NA = not available.
**Information values.*
***Provisional values.*

Table 28.1, ***continued.***

Material	Provider	Description	Pb (ppm)	Pr (ppm)	Rb (ppm)	Sb (ppm)	Sc (ppm)	Sm (ppm)
In-house Reference Materials								
LK-NIP-1	In-house	Diabase Sill	3.9 ± 1.8 (18)	2.55 ± 0.05 (18)	13.0 ± 0.5 (18)	0.070 ± 0.014 (18)	32.9 ± 1.0 (18)	3.14 ± 0.07 (18)
MRB-29	In-house	Basalt	4.9 ± 1.6 (943)	6.47 ± 0.21 (943)	14.4 ± 0.6 (943)	0.07 ± 0.04 (943)	32.6 ± 1.4 (943)	6.18 ± 0.21 (943)
ODL-1	In-house	Dolomitic Limestone	17.5 ± 0.4 (118)	3.90 ± 0.11 (118)	23.4 ± 1.0 (118)	0.23 ± 0.05 (118)	3.0 ± 0.5 (118)	3.17 ± 0.12 (118)
QS-1	In-house	Calcareous Shale	9.0 ± 0.3 (5)	9.54 ± 0.17 (5)	132 ± 6 (5)	0.748 ± 0.020 (5)	13.0 ± 1.2 (5)	7.02 ± 0.09 (5)
RV-1	In-house	Melagabbro	5.05 ± 0.13 (5)	0.911 ± 0.018 (5)	19.5 ± 0.5 (5)	0.058 ± 0.012 (5)	27.5 ± 0.7 (5)	0.83 ± 0.04 (5)
Certified Reference Materials								
AGV-2	USGS	Andesite	12.9 ± 0.5 (373)	8.1 ± 0.3 (373)	66.9 ± 2.9 (373)	0.48 ± 0.08 (373)	12.5 ± 0.7 (373)	5.47 ± 0.23 (373)
Certificate‡			*13 ± 1*	*8.3 ± 0.6*	*68.6 ± 2.3*	*0.6**	*13 ± 1*	*5.7 ± 0.3**
BHVO-2	USGS	Basalt	1.67 ± 0.20 (294)	5.37 ± 0.18 (294)	9.1 ± 0.4 (294)	0.12 ± 0.03 (294)	32.1 ± 1.4 (294)	6.15 ± 0.23 (294)
Certificate‡			*NA*	*NA*	*9.8 ± 1.0*	*NA*	*32 ± 1*	*6.2 ± 0.4*
GSP-2	USGS	Granodiorite	40.6 ± 1.2 (279)	55.7 ± 2.0 (279)	242 ± 11 (279)	0.39 ± 0.07 (279)	6.4 ± 0.9 (279)	26.2 ± 1.0 (279)
Certificate‡			*42 ± 3*	*51 ± 5**	*245 ± 7*	*NA*	*6.3 ± 0.7*	*27 ± 1*
GSR-6	IGGE	Limestone	15.0 ± 0.9 (111)	3.08 ± 0.09 (111)	32.3 ± 1.2 (111)	0.54 ± 0.06 (111)	6.2 ± 0.7 (111)	2.21 ± 0.08 (111)
Certificate†			*18 ± 3*	*3.4 ± 0.4*	*32 ± 4*	*0.43 ± 0.11*	*6.0 ± 1.1*	*2.4 ± 0.2*
OKUM-1	IAG	Ultramafic Komatiite	0.33 ± 0.12 (52)	0.234 ± 0.010 (52)	0.92 ± 0.07 (52)	0.078 ± 0.010 (52)	28.3 ± 0.9 (52)	0.68 ± 0.04 (52)
Certificate‡			*0.26 ± 0.02*	*0.235 ± 0.008*	*0.96 ± 0.06*	*0.076 ± 0.012**	*27.9 ± 1.5*	*0.715 ± 0.011*
SU-1b	CANMET	Ni-Cu-Co Ore	55.6 ± 0.8 (3)	4.36 ± 0.28 (3)	12.3 ± 1.0 (3)	0.260 ± 0.028 (3)	8.17 ± 0.09 (3)	3.03 ± 0.21 (3)
Certificate‡			*58 ± 5*	*NA*	*NA*	*NA*	*NA*	*NA*
SY-4	CANMET	Diorite Gneiss	9.51 ± 0.11 (4)	15.11 ± 0.27 (4)	53.1 ± 2.0 (4)	0.019 ± 0.005 (4)	1.12 ± 0.19 (4)	12.98 ± 0.31 (4)
Certificate‡			*10 ± 1*	*15.0 ± 0.3*	*55 ± 1.5*	*0.01 – 0.3**	*1.1 ± 0.1*	*12.7 ± 0.4*

Notes: *Compiled data given as mean ± 1 standard deviation of results (number of measurements).*
‡ = Certificate value is average ± 1 standard deviation of the laboratory means.
† = Certificate value is average ± 99% confidence interval on the population mean.
‡ = Certificate value is average ± 95% confidence interval on the population mean.
Abbreviations: *CANMET = Canada Centre for Mineral and Energy Technology; IAG = International Association of Geoanalysts; IGGE = Institute of Geophysical and Geochemical Exploration, China; USGS = United States Geological Survey.*
NA = not available.
**Information values.*
***Provisional values.*

Table 28.1, ***continued.***

Material	Provider	Description	Sn (ppm)	Sr (ppm)	Ta (ppm)	Tb (ppm)	Th (ppm)	Ti (ppm)
In-house Reference Materials								
LK-NIP-1	In-house	Diabase Sill	0.76 ± 0.08 (18)	163.2 ± 3.1 (18)	0.290 ± 0.008 (18)	0.630 ± 0.019 (18)	1.57 ± 0.05 (18)	6,826 ± 230 (18)
MRB-29	In-house	Basalt	2.3 ± 0.9 (943)	306 ± 9 (943)	0.78 ± 0.04 (943)	0.89 ± 0.04 (943)	2.56 ± 0.09 (943)	11,490 ± 430 (943)
ODL-1	In-house	Dolomitic Limestone	0.37 ± 0.05 (118)	68.5 ± 1.6 (118)	0.137 ± 0.010 (118)	0.409 ± 0.016 (118)	1.98 ± 0.09 (118)	619 ± 31 (118)
QS-1	In-house	Calcareous Shale	2.49 ± 0.21 (5)	110.8 ± 1.7 (5)	0.92 ± 0.04 (5)	0.89 ± 0.03 (5)	10.8 ± 0.5 (5)	4,524 ± 133 (5)
RV-1	In-house	Melagabbro	0.308 ± 0.016 (5)	337.0 ± 3.1 (5)	0.0575 ± 0.0019 (5)	0.147 ± 0.004 (5)	0.95 ± 0.10 (5)	1,218 ± 24 (5)
Certified Reference Materials								
AGV-2	USGS	Andesite	1.93 ± 0.23 (373)	642 ± 18 (373)	0.81 ± 0.10 (373)	0.616 ± 0.029 (373)	6.01 ± 0.23 (373)	6,087 ± 233 (373)
*Certificate*ǂ			*2.3 ± 0.4**	*658 ± 17*	*0.89 ± 0.08**	*0.64 ± 0.04**	*6.1 ± 0.6*	*NA*
BHVO-2	USGS	Basalt	1.64 ± 0.16 (294)	388 ± 12 (294)	1.11 ± 0.04 (294)	0.94 ± 0.04 (294)	1.21 ± 0.05 (294)	16,260 ± 550 (294)
*Certificate*ǂ			*1.9**	*389 ± 23*	*1.4**	*0.9**	*1.9**	*NA*
GSP-2	USGS	Granodiorite	6.3 ± 0.5 (279)	233 ± 8 (279)	0.84 ± 0.03 (279)	1.26 ± 0.06 (279)	104 ± 14 (279)	3,898 ± 157 (279)
*Certificate*ǂ			*NA*	*240 ± 10*	*NA*	*NA*	*NA*	*NA*
GSR-6	IGGE	Limestone	1.10 ± 0.10 (111)	927 ± 28 (111)	0.406 ± 0.022 (111)	0.277 ± 0.011 (111)	3.8 ± 0.3 (111)	1,899 ± 93 (111)
Certificate†			*0.98**	*913 ± 54*	*0.42 ± 0.05*	*0.35 ± 0.05*	*4.1 ± 0.5*	*1,960 ± 90*
OKUM-1	IAG	Ultramafic Komatiite	0.17 ± 0.06 (52)	15.8 ± 0.5 (52)	0.0205 ± 0.0026 (52)	0.221 ± 0.008 (52)	0.032 ± 0.006 (52)	2,201 ± 81 (52)
Certificate‡			*0.25 ± 0.02*	*16.1 ± 1.0*	*0.0264 ± 0.0038*	*0.229 ± 0.010**	*0.031 ± 0.004*	*NA*
SU-1b	CANMET	Ni-Cu-Co Ore	1.0 ± 0.3 (3)	278 ± 13 (3)	0.1411 ± 0.0013 (3)	0.280 ± 0.014 (3)	1.248 ± 0.012 (3)	2,165 ± 7 (3)
Certificate‡			*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
SY-4	CANMET	Diorite Gneiss	7.6 ± 1.6 (4)	1,155 ± 18 (4)	0.86 ± 0.04 (4)	2.66 ± 0.10 (4)	1.32 ± 0.09 (4)	1,624 ± 47 (4)
Certificate‡			*7.1 ± 0.6***	*1,191 ± 12*	*0.9 ± 0.1*	*2.6 ± 0.1*	*1.4 ± 0.2*	*NA*

Notes: *Compiled data given as mean ± 1 standard deviation of results (number of measurements).*
ǂ *= Certificate value is average ± 1 standard deviation of the laboratory means.*
† *= Certificate value is average ± 99% confidence interval on the population mean.*
‡ *= Certificate value is average ± 95% confidence interval on the population mean.*
Abbreviations: *CANMET = Canada Centre for Mineral and Energy Technology; IAG = International Association of Geoanalysts; IGGE = Institute of Geophysical and Geochemical Exploration, China; USGS = United States Geological Survey.*
NA = not available.
**Information values.*
***Provisional values.*

Table 28.1, ***continued.***

Material	Provider	Description	Tl (ppm)	Tm (ppm)	U (ppm)	V (ppm)	W (ppm)	Y (ppm)
In-house Reference Materials								
LK-NIP-1	In-house	Diabase Sill	0.089 ± 0.003 (18)	0.341 ± 0.007 (18)	0.459 ± 0.015 (18)	288 ± 10 (18)	0.322 ± 0.017 (18)	22.5 ± 0.3 (18)
MRB-29	In-house	Basalt	0.072 ± 0.004 (942)	0.387 ± 0.017 (943)	0.634 ± 0.028 (943)	318 ± 13 (933)	0.209 ± 0.015 (943)	26.8 ± 0.7 (943)
ODL-1	In-house	Dolomitic Limestone	0.404 ± 0.018 (118)	0.142 ± 0.006 (118)	0.84 ± 0.04 (118)	17.7 ± 0.8 (118)	0.288 ± 0.027 (118)	12.60 ± 0.28 (118)
QS-1	In-house	Calcareous Shale	0.67 ± 0.03 (4)	0.419 ± 0.021 (5)	2.61 ± 0.11 (5)	113 ± 3 (5)	1.26 ± 0.04 (5)	28.0 ± 1.5 (5)
RV-1	In-house	Melagabbro	0.130 ± 0.007 (5)	0.0956 ± 0.0017 (5)	0.480 ± 0.024 (5)	110 ± 4 (5)	0.25 ± 0.06 (5)	5.76 ± 0.11 (5)
Certified Reference Materials								
AGV-2	USGS	Andesite	0.273 ± 0.011 (372)	0.254 ± 0.012 (373)	1.88 ± 0.08 (373)	120 ± 5 (369)	0.499 ± 0.028 (373)	19.0 ± 0.6 (373)
*Certificate*ǂ			*0.27**	*0.26 ± 0.02**	*1.88 ± 0.16*	*120 ± 5*	*NA*	*20 ±1*
BHVO-2	USGS	Basalt	0.0203 ± 0.0019 (294)	0.336 ± 0.015 (294)	0.423 ± 0.018 (294)	329 ± 12 (290)	0.219 ± 0.016 (294)	25.6 ± 0.7 (294)
*Certificate*ǂ			*NA*	*NA*	*NA*	*317 ± 11*	*NA*	*26 ± 2*
GSP-2	USGS	Granodiorite	1.31 ± 0.05 (279)	0.287 ± 0.014 (279)	2.45 ± 0.11 (279)	52.8 ± 2.1 (278)	0.36 ± 0.03 (279)	26.1 ± 0.8 (279)
*Certificate*ǂ			*1.1**	*0.29 ± 0.02**	*2.40 ± 0.19*	*52 ± 4*	*NA*	*28 ± 2*
GSR-6	IGGE	Limestone	0.303 ± 0.018 (111)	0.130 ± 0.005 (111)	1.88 ± 0.07 (111)	38.5 ± 1.9 (111)	0.87 ± 0.07 (111)	8.82 ± 0.25 (111)
Certificate†			*0.33 ± 0.07*	*0.17 ± 0.04*	*1.9 ± 0.3*	*36 ± 6*	*0.67 ± 0.18*	*9.1 ± 1.6*
OKUM-1	IAG	Ultramafic Komatiite	0.0146 ± 0.0012 (52)	0.150 ± 0.007 (52)	0.0116 ± 0.0012 (52)	172 ± 6 (51)	0.061 ± 0.008 (52)	9.16 ± 0.24 (52)
Certificate‡			*NA*	*0.155 ± 0.006**	*0.012 ± 0.005*	*167.8 ± 3.1*	*NA*	*9.08 ± 0.29*
SU-1b	CANMET	Ni-Cu-Co Ore	0.302 ± 0.007 (3)	0.104 ± 0.007 (3)	0.207 ± 0.020 (3)	84.4 ± 2.1 (3)	0.432 ± 0.028 (3)	7.01 ± 0.24 (3)
Certificate‡			*NA*	*NA*	*NA*	*82.5 ± 4.4***	*NA*	*NA*
SY-4	CANMET	Diorite Gneiss	0.265 ± 0.013 (4)	2.31 ± 0.09 (4)	0.93 ± 0.06 (4)	5.33 ± 0.18 (4)	0.035 ± 0.015 (4)	118 ± 3 (4)
Certificate‡			*0.2 – 0.5**	*2.3 ± 0.1*	*0.8 ± 0.1*	*8 ± 1.6*	*0.2 ± 15**	*119 ± 2*

Notes: *Compiled data given as mean ± 1 standard deviation of results (number of measurements).*
ǂ *= Certificate value is average ± 1 standard deviation of the laboratory means.*
† *= Certificate value is average ± 99% confidence interval on the population mean.*
‡ *= Certificate value is average ± 95% confidence interval on the population mean.*
Abbreviations: *CANMET = Canada Centre for Mineral and Energy Technology; IAG = International Association of Geoanalysts; IGGE = Institute of Geophysical and Geochemical Exploration, China; USGS = United States Geological Survey.*
NA = not available.
**Information values.*
***Provisional values*

Table 28.1, ***continued.***

Material	Provider	Description	Yb (ppm)	Zn (ppm)	Zr (ppm)
In-house Reference Materials					
LK-NIP-1	In-house	Diabase Sill	2.19 ± 0.06 (18)	101 ± 4 (18)	85.3 ± 2.7 (18)
MRB-29	In-house	Basalt	2.44 ± 0.10 (943)	107 ± 6 (943)	173 ± 5 (943)
ODL-1	In-house	Dolomitic Limestone	0.85 ± 0.03 (118)	56.7 ± 2.5 (118)	28.1 ± 2.3 (118)
QS-1	In-house	Calcareous Shale	2.75 ± 0.15 (5)	74.7 ± 2.5 (5)	149 ± 8 (5)
RV-1	In-house	Melagabbro	0.675 ± 0.018 (5)	98.6 ± 2.2 (5)	17.5 ± 1.9 (5)
Certified Reference Materials					
AGV-2	USGS	Andesite	1.63 ± 0.07 (373)	88 ± 3 (373)	233 ± 13 (373)
*Certificate*ǂ			*1.6 ± 0.2*	*86 ± 8*	*230 ± 4*
BHVO-2	USGS	Basalt	2.02 ± 0.08 (294)	100 ± 7 (294)	172 ± 5 (294)
*Certificate*ǂ			*2.0 ± 0.2**	*103 ± 6*	*172 ± 11*
GSP-2	USGS	Granodiorite	1.67 ± 0.07 (279)	114 ± 6 (279)	509 ± 34 (279)
*Certificate*ǂ			*1.6 ± 0.2*	*120 ± 10*	*550 ± 30*
GSR-6	IGGE	Limestone	0.846 ± 0.028 (111)	47.8 ± 2.3 (111)	60.5 ± 2.1 (111)
Certificate†			*0.90 ± 0.11*	*52 ± 4*	*62 ± 13*
OKUM-1	IAG	Ultramafic Komatiite	0.97 ± 0.03 (52)	64.1 ± 1.8 (52)	18.2 ± 1.1 (52)
Certificate‡			*1.009 ± 0.023*	*61.2 ± 1.9*	*17.0 ± 1.4*
SU-1b	CANMET	Ni-Cu-Co Ore	0.63 ± 0.05 (3)	258.3 ± 2.9 (3)	82.6 ± 2.5 (3)
Certificate‡			*NA*	*235 ± 19*	*NA*
SY-4	CANMET	Diorite Gneiss	15.2 ± 0.5 (4)	94.2 ± 1.9 (4)	458 ± 37 (4)
Certificate‡			*14.8 ± 0.4*	*93 ± 2*	*517 ± 16*

Notes: *Compiled data given as mean ± 1 standard deviation of results (number of measurements).*
ǂ *= Certificate value is average ± 1 standard deviation of the laboratory means.*
† *= Certificate value is average ± 99% confidence interval on the population mean.*
‡ *= Certificate value is average ± 95% confidence interval on the population mean.*
Abbreviations: *CANMET = Canada Centre for Mineral and Energy Technology; IAG = International Association of Geoanalysts; IGGE = Institute of Geophysical and Geochemical Exploration, China; USGS = United States Geological Survey.*
NA = not available.
**Information values.*
***Provisional values.*

Table 28.2. Summary of results obtained by the IMO-100 test method for in-house and certified reference materials from September 13, 2017, to July 7, 2022.

Material	Provider	Description	Ba (ppm)	Be (ppm)	Bi (ppm)	Cd (ppm)
In-house Reference Materials						
MRB-29	In-house	Basalt	287 ± 5 (18)	0.99 ± 0.11 (18)	0.0274 ± 0.0020 (18)	0.103 ± 0.012 (18)
Certified Reference Materials						
AGV-2	USGS	Andesite	1,131 ± 14 (14)	2.05 ± 0.09 (14)	0.054 ± 0.012 (14)	0.073 ± 0.009 (14)
*Certificate*ǂ			*1,140 ± 32*	*2.3 ± 0.4*	*NA*	*NA*
BHVO-2	USGS	Basalt	133 ± 3 (3)	1.00 ± 0.14 (3)	0.027 ± 0.022 (3)	0.106 ± 0.028 (3)
*Certificate*ǂ			*130 ± 13*	*NA*	*NA*	*NA*

Material	Provider	Description	Ce (ppm)	Co (ppm)	Cr (ppm)	Cs (ppm)
In-house Reference Materials						
MRB-29	In-house	Basalt	48.0 ± 0.8 (18)	52.9 ± 2.0 (18)	275 ± 9 (18)	0.245 ± 0.006 (18)
Certified Reference Materials						
AGV-2	USGS	Andesite	68.3 ± 1.0 (14)	16.5 ± 0.7 (14)	16.7 ± 0.5 (14)	1.157 ± 0.031 (14)
*Certificate*ǂ			*68 ± 3*	*16 ± 1*	*17 ± 2*	*1.16 ± 0.08**
BHVO-2	USGS	Basalt	37.5 ± 0.6 (3)	45.9 ± 0.8 (3)	292 ± 5 (3)	0.0968 ± 0.0017 (3)
*Certificate*ǂ			*NA*	*45 ± 3*	*280 ± 19*	*NA*

Material	Provider	Description	Cu (ppm)	Dy (ppm)	Er (ppm)	Eu (ppm)
In-house Reference Materials						
MRB-29	In-house	Basalt	145 ± 7 (18)	5.21 ± 0.18 (18)	2.80 ± 0.08 (18)	1.89 ± 0.07 (18)
Certified Reference Materials						
AGV-2	USGS	Andesite	49.9 ± 1.9 (14)	3.47 ± 0.08 (14)	1.84 ± 0.06 (14)	1.54 ± 0.05 (14)
*Certificate*ǂ			*53 ± 4*	*3.6 ± 0.2*	*1.79 ± 0.11**	*1.54 ± 0.10*
BHVO-2	USGS	Basalt	132.1 ± 1.7 (3)	5.32 ± 0.28 (3)	2.51 ± 0.08 (3)	2.07 ± 0.08 (3)
*Certificate*ǂ			*127 ± 7*	*NA*	*NA*	*NA*

Material	Provider	Description	Ga (ppm)	Gd (ppm)	Hf (ppm)	Ho (ppm)
In-house Reference Materials						
MRB-29	In-house	Basalt	19.6 ± 0.3 (18)	5.97 ± 0.18 (18)	4.35 ± 0.10 (18)	1.01 ± 0.04 (18)
Certified Reference Materials						
AGV-2	USGS	Andesite	20.4 ± 0.4 (14)	4.56 ± 0.14 (14)	5.14 ± 0.11 (14)	0.660 ± 0.016 (14)
*Certificate*ǂ			*20 ± 1*	*4.69 ± 0.26***	*5.08 ± 0.20**	*0.71 ± 0.08**
BHVO-2	USGS	Basalt	21.1 ± 0.4 (3)	6.18 ± 0.26 (3)	4.40 ± 0.09 (3)	0.973 ± 0.025 (3)
*Certificate*ǂ			*21.7 ± 0.9*	*6.3 ± 0.2**	*4.1 ± 0.3*	*1.04 ± 0.04**

Material	Provider	Description	In (ppm)	La (ppm)	Li (ppm)	Lu (ppm)
In-house Reference Materials						
MRB-29	In-house	Basalt	0.0768 ± 0.0030 (18)	21.6 ± 0.5 (18)	10.1 ± 0.3 (18)	0.351 ± 0.014 (18)
Certified Reference Materials						
AGV-2	USGS	Andesite	0.0443 ± 0.0018 (14)	37.5 ± 0.4 (14)	10.13 ± 0.28 (14)	0.248 ± 0.009 (14)
*Certificate*ǂ			*NA*	*38 ± 1*	*11**	*0.25 ± 0.01**
BHVO-2	USGS	Basalt	0.083 ± 0.004 (3)	15.44 ± 0.16 (3)	4.26 ± 0.06 (3)	0.275 ± 0.008 (3)
*Certificate*ǂ			*NA*	*15 ± 1*	*5**	*0.28 ± 0.01**

Notes: *Compiled data given as mean ± 1 standard deviation of results (number of measurements).*
ǂ *= Certificate value is average ± 1 standard deviation of the laboratory means.*
Abbreviations: *USGS = United States Geological Survey; NA = not available.*
**Information values.*
***Provisional values.*

Table 28.2, *continued*.

Material	Provider	Description	Mo (ppm)	Nb (ppm)	Nd (ppm)	Ni (ppm)
In-house Reference Materials						
MRB-29	In-house	Basalt	0.76 ± 0.05 (18)	12.5 ± 0.3 (18)	27.7 ± 0.6 (18)	114 ± 5 (18)
Certified Reference Materials						
AGV-2	USGS	Andesite	1.95 ± 0.10 (14)	13.3 ± 0.5 (14)	30.7 ± 0.6 (14)	18.9 ± 0.6 (14)
Certificate‡			*NA*	*15 ± 1*	*30 ± 2*	*19 ± 3*
BHVO-2	USGS	Basalt	4.9 ± 0.6 (3)	17.38 ± 0.13 (3)	24.9 ± 0.5 (3)	120.8 ± 1.7 (3)
Certificate‡			*NA*	*18 ± 2**	*25.0 ± 1.8*	*119 ± 7*

Material	Provider	Description	Pb (ppm)	Pr (ppm)	Rb (ppm)	Sb (ppm)
In-house Reference Materials						
MRB-29	In-house	Basalt	4.68 ± 0.15 (18)	6.43 ± 0.19 (18)	14.4 ± 0.6 (18)	0.08 ± 0.06 (18)
Certified Reference Materials						
AGV-2	USGS	Andesite	12.96 ± 0.26 (14)	8.09 ± 0.21 (14)	66.8 ± 2.3 (14)	0.48 ± 0.08 (14)
Certificate‡			*13 ± 1*	*8.3 ± 0.6*	*68.6 ± 2.3*	*0.6**
BHVO-2	USGS	Basalt	1.58 ± 0.12 (3)	5.40 ± 0.07 (3)	9.4 ± 0.3 (3)	0.112 ± 0.011 (3)
Certificate‡			*NA*	*NA*	*9.8 ± 1.0*	*NA*

Material	Provider	Description	Sc (ppm)	Sm (ppm)	Sn (ppm)	Sr (ppm)
In-house Reference Materials						
MRB-29	In-house	Basalt	32.9 ± 1.0 (18)	6.14 ± 0.21 (18)	2.19 ± 0.21 (18)	306 ± 5 (18)
Certified Reference Materials						
AGV-2	USGS	Andesite	12.7 ± 0.5 (14)	5.47 ± 0.19 (14)	1.93 ± 0.19 (14)	640 ± 14 (14)
Certificate‡			*13 ± 1*	*5.7 ± 0.3**	*2.3 ± 0.4**	*658 ± 17*
BHVO-2	USGS	Basalt	31.6 ± 1.0 (3)	6.06 ± 0.25 (3)	1.78 ± 0.11 (3)	387 ± 5 (3)
Certificate‡			*32 ± 1*	*6.2 ± 0.4*	*1.9**	*389 ± 23*

Material	Provider	Description	Ta (ppm)	Tb (ppm)	Th (ppm)	Ti (ppm)
In-house Reference Materials						
MRB-29	In-house	Basalt	0.773 ± 0.028 (18)	0.884 ± 0.028 (18)	2.56 ± 0.06 (18)	11,550 ± 271 (18)
Certified Reference Materials						
AGV-2	USGS	Andesite	0.801 ± 0.021 (14)	0.615 ± 0.025 (14)	6.02 ± 0.19 (14)	6,111 ± 172 (14)
Certificate‡			*0.89 ± 0.08**	*0.64 ± 0.04**	*6.1 ± 0.6*	*NA*
BHVO-2	USGS	Basalt	1.13 ± 0.06 (3)	0.91 ± 0.03 (3)	1.23 ± 0.04 (3)	16,214 ± 209 (3)
Certificate‡			*1.4**	*0.9**	*1.2 ± 0.3**	*NA*

Material	Provider	Description	Tl (ppm)	Tm (ppm)	U (ppm)	V (ppm)
In-house Reference Materials						
MRB-29	In-house	Basalt	0.073 ± 0.004 (18)	0.384 ± 0.010 (18)	0.631 ± 0.018 (18)	320 ± 7 (18)
Certified Reference Materials						
AGV-2	USGS	Andesite	0.276 ± 0.009 (14)	0.257 ± 0.009 (14)	1.86 ± 0.06 (14)	119.7 ± 2.3 (14)
Certificate‡			*0.27**	*0.26 ± 0.02**	*1.88 ± 0.16*	*120 ± 5*
BHVO-2	USGS	Basalt	0.0190 ± 0.0012 (3)	0.327 ± 0.010 (3)	0.407 ± 0.009 (3)	327 ± 8 (3)
Certificate‡			*NA*	*NA*	*NA*	*317 ± 11*

Notes: *Compiled data given as mean ± 1 standard deviation of results (number of measurements).*
‡ = Certificate value is average ± 1 standard deviation of the laboratory means.
Abbreviations: *USGS = United States Geological Survey; NA = not available.*
**Information values.*
***Provisional values.*

Table 28.2, *continued*.

Material	Provider	Description	W (ppm)	Y (ppm)	Yb (ppm)	Zn (ppm)
In-house Reference Materials						
MRB-29	In-house	Basalt	0.205 ± 0.010 (18)	26.7 ± 0.4 (18)	2.41 ± 0.06 (18)	106.1 ± 2.4 (18)
Certified Reference Materials						
AGV-2	USGS	Andesite	0.496 ± 0.016 (14)	19.1 ± 0.3 (14)	1.64 ± 0.06 (14)	88.1 ± 2.4 (14)
Certificateǂ			*NA*	*20 ±1*	*1.6 ± 0.2*	*86 ± 8*
BHVO-2	USGS	Basalt	0.222 ± 0.007 (3)	25.63 ± 0.04 (3)	1.96 ± 0.05 (3)	101.7 ± 1.5 (3)
Certificateǂ			*NA*	*26 ± 2*	*2.0 ± 0.2**	*103 ± 6*

Material	Provider	Description	Zr (ppm)
In-house Reference Materials			
MRB-29	In-house	Basalt	173 ± 4 (18)
Certified Reference Materials			
AGV-2	USGS	Andesite	236 ± 5 (14)
Certificateǂ			*230 ± 4*
BHVO-2	USGS	Basalt	170 ± 6 (3)
Certificateǂ			*172 ± 11*

Notes: *Compiled data given as mean ± 1 standard deviation of results (number of measurements).*
ǂ = Certificate value is average ± 1 standard deviation of the laboratory means.
Abbreviations: *USGS = United States Geological Survey; NA = not available.*
**Information values.*
***Provisional values.*

Table 28.3. Summary of results obtained by the IMP-101 test method for in-house and certified reference materials from October 1, 2018, to July 7, 2022.

Material	Provider	Description	Au (ppm)	Pd (ppm)	Pt (ppm)
In-house Reference Materials					
LDI-1	In-house	Gabbro	85 ± 18 (132)	826 ± 41 (132)	91 ± 9 (132)
LK-NIP-1	In-house	Diabase	6 ± 8 (111)	16.3 ± 1.8 (111)	12.1 ± 0.8 (111)
Certified Reference Materials					
OKUM-1	IAG	Ultramafic Komatiite	1.6 ± 0.4 (11)	9.8 ± 0.9 (11)	9.5 ± 0.6 (11)
Reference†			*1.41 ± 0.19*	*11.83 ± 0.14*	*11.4 ± 0.8*
TDB-1	CANMET	Diabase	6.6 ± 1.6 (37)	21.0 ± 1.8 (37)	4.5 ± 0.5 (37)
Certificate‡			*6.3 ± 1.0*	*22.4 ± 1.4*	*5.8 ± 1.1*
UMT-1	CANMET	Ultramafic Ore Tailings	45 ± 5 (113)	94 ± 13 (113)	119 ± 14 (113)
Certificate‡			*48 ± 2*	*106 ± 3*	*129 ± 5*
WGB-1	CANMET	Gabbro	2.4 ± 1.1 (92)	11.8 ± 2.5 (92)	4.9 ± 1.9 (92)
Certificate‡			*2.9 ± 1.1*	*13.9 ± 2.1*	*6.1 ± 1.6*
WPR-1	CANMET	Altered Peridotite	43 ± 5 (5)	217 ± 17 (5)	269 ± 7 (5)
Certificate‡			*42.2 ± 2.8*	*235 ± 9*	*285 ± 12*

Notes: *Compiled data given as mean ± 1 standard deviation of results (number of measurements).*
†Consensus value from GeoRem database of published values (http://georem.mpch-mainz.gwdg.de, accessed Sept 27th, 2022). Median ± 1 standard deviation.
‡Certificate values are average ± 95% confidence interval on the population mean.
NA = not available.
Abbreviations: *CANMET = Canadian Centre for Mineral and Energy Technology; IAG = International Association of Geoanalysts.*

29. Revision of the Calibration for Trace Element Analysis of Geological Samples by Wavelength Dispersive X-Ray Fluorescence at the Geoscience Laboratories



G.L. Keating[1]

[1]Geoscience Laboratories, Ontario Geological Survey

INTRODUCTION

In 2019, the replacement of the 2 aging Panalytical® Axios® wavelength dispersive X-ray fluorescence (WD-XRF) spectrometers was initiated. As a result, the first instrument was replaced in September 2020 and the second one in March 2021. Each was replaced with a Malvern Panalytical® Zetium® with dual cores: wavelength dispersive and energy dispersive. The existing WD-XRF methods then needed to be built on the new spectrometers. The first methods to be built were the trace element analyses: XRF-T02 and XRF-T03.

The building of the trace element methods presented an opportunity to address sample preparation issues and expand the capabilities of the methods. An amide wax–based dry binder is now used to prepare pressed pellets of samples. Pressed pellets are ready to run immediately on the spectrometer as soon as they are unloaded from the pellet press die and labelled.

The new calibrations are based on the same correction techniques (mass absorption and overlaps) as the previous methods and are as robust for the 24 previously offered analytes. Titanium (Ti) was added as a new analyte to XRF-T03 for low concentrations that is, less than 4500 ppm Ti.

As part of the new build of the trace element analytical applications, the lower limits of detection (LLoD), lower limits of reporting (LLoR) and the upper limits for reporting (UL) were re-evaluated. The final evaluation of the new methods was completed in February 2022.

BACKGROUND

Trace element analysis using WD-XRF is particularly sensitive to matrix, grain-size and oxidation state effects. Matrix effects are usually the most significant and the most difficult to correct for most types of geological samples. The new applications for the methods use Pro-Trace in combination with synthetic standards and a wide range of interlaboratory geological reference materials to enhance LLoDs, empirically determine mass absorption and overlap corrections, and maintain the overall robustness of the applications. Sample preparation of pressed pellets was modified by changing from a water-based binder to a dry, amide wax, non-hazardous binder. The dry binder is compatible with all types of geological samples, including hygroscopic minerals, and its use makes it more efficient and easier to prepare and run samples for trace elements.

Summary of Field Work and Other Activities, 2022,
Ontario Geological Survey, Open File Report 6390, p.29-1 to 29-7.

© King's Printer for Ontario, 2022

With any change to a calibration or instrumentation, it is mandatory to verify the performance of the methods and update the statistics and limits as necessary. This article presents a summary of the work done to build the new calibrations and determine the revised figures of merit for the methods based on those calibrations.

ANALYTICAL WORK

The new spectrometer measuring applications were built based on parameters provided by the instrument manufacturer (Malvern Panalytical®) and those in use by Geo Labs in the previous method versions. The methods XRF-T02 and XRF-T03 use a mass attenuation calibration technique (PANalytical 2006; Willis and Duncan 2008) based on empirical measurements of expected matrices with corrections for tube lines (from tube contamination), determination of baselines and interference overlaps.

The measuring parameters are based on the previously successful applications used in the Geoscience Laboratories. Molybdenum (Mo) is measured and calibrated against Rh Compton scatter line. Zinc (Zn), copper (Cu), nickel (Ni), iron (Fe), chromium (Cr), titanium (Ti), calcium (Ca) and potassium (K) K_β lines are used for mass absorption corrections. Bismuth (Bi), Ca, Fe, germanium (Ge), hafnium (Hf), iodine (I), K, neodymium (Nd), Ti, antimony (Sb), selenium (Se), tin (Sn), tantalum (Ta), tungsten (W) and ytterbium (Yb) are measured for overlap corrections, in addition to the overlaps from other analytes, but are not reported.

All the measuring parameters were carefully optimized based on the types of samples received in past and anticipated projects. Altogether, 25 analytes are measured for quantification with XRF-T02 and XRF-T03 methods: arsenic (As), barium (Ba), bromine (Br), cerium (Ce), cobalt (Co), chromium (Cr), cesium (Cs), copper (Cu), gallium (Ga), lanthanum (La), manganese (Mn), molybdenum (Mo), niobium (Nb), nickel (Ni), lead (Pb), rubidium (Rb), scandium (Sc), strontium (Sr), thorium (Th), titanium (Ti), uranium (U), vanadium (V), yttrium (Y), zinc (Zn) and zirconium (Zr).

A total of 123 certified reference materials (CRMs) were used to calibrate the spectrometer, along with 69 synthetic materials purchased from Malvern Panalytical® or made in-house from high purity materials. Whenever possible or necessary, new preparations of CRMs were made to ensure infinite thickness and robust pressed pellets.

An independent set of 39 CRMs (AGV-2, AMIS013, AMIS073, AMIS085, AMIS098, BHVO-2, BX-N, CG-2, CHR-PT+, COQ-1, ECRM879-1, FK-N, GSD-11, GS-N, GSP-2, GXR-4, HARZ-01, MGR-N, MU-H, NIM-L, NIST2710, NIST8608, NKT-1, NOD-P-1, OKUM-1, ORCA-1, OREAS 600, OREAS 601, OREAS 753, OU-8, OU-9, QS-1, STSD-1, STSD-2, SY-4, TDB-1, WMG-1A, WMS-1A, WPR-1A) with a wide variety of compositions and analyte concentrations were freshly prepared using the same protocol as that applied to samples. These materials were measured multiple times (>12 times each) between September 2021 and February 2022. The results were used to check the calibration regressions for accuracy for all 25 elements over the range of analysis. A summary of the figures of merit obtained from the CRM analyses is provided in Table 29.2 (XRF-T02) and Table 29.3 (XRF-T03).

METHOD VERIFICATION

The LLoDs were estimated using measurements obtained between September and December 2021 of 169 client samples and CRMs that had routinely been prepared in duplicate in the Geo Labs. By using duplicate analyses carried out on separate sample aliquots and analyzed on different days, it was possible to obtain an estimate of the overall "method" uncertainty as a function of concentration for each analyte that includes most of the major sources of variation (including those from sample preparation and within-

run or between-run instrumental variations) and from which the method LLoD can be calculated. The sample pairs were chosen to represent a broad range of rock types and, as much as possible, to ensure all sample types were represented over the entire desired range of analysis. The uncertainty and LLoD calculations were based on the seminal article published by Thompson and Howarth (1976).

The data were grouped into 13 groups of 13 sample pairs, each sample pair averaged, and relative difference calculated. For each group, the mean concentration, group median difference, relative difference (%) and expected difference (95% relative uncertainty) were calculated. The LLoDs and optimal precisions that are achievable by the method were estimated from the regression of median differences against the group means. To minimize the effect of the highest concentration groups on the regression and the uncertainty in the calculated LLoDs, only the lowest concentration groups (points closest to the LLoD) were used to calculate the LLoDs for most elements. In most cases, at least 11 groups (143 sample pairs) were used in the calculation, but as few as 6 or 9 groups (78 to 117 samples) were used for some elements. A typical set of plots (Cr) used to evaluate the LLoD statistics for the data are shown in Figure 29.1. The final LLoDs and best precisions for XRF-T02 and XRF-T03 analytes are listed in Table 29.1 along with the number of groups used in their estimation.

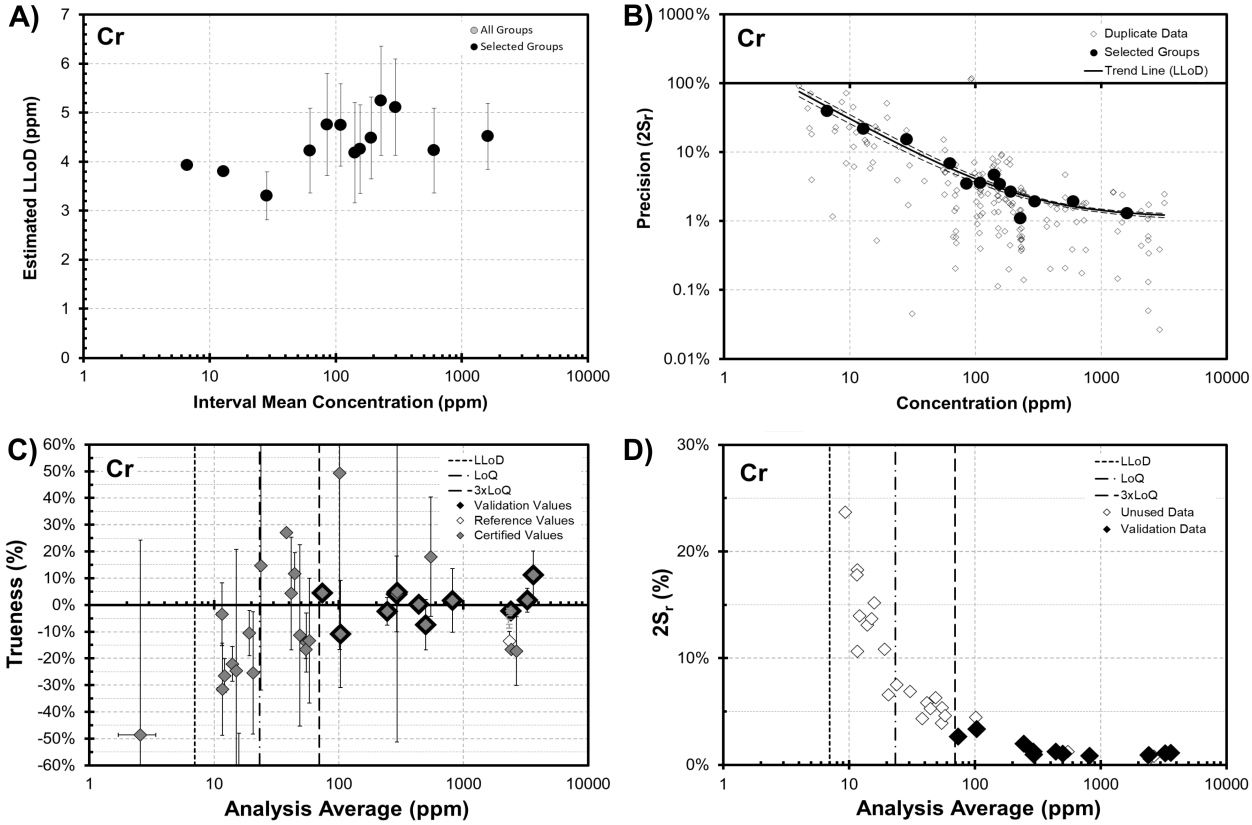


Figure 29.1. Plots summarizing the data used for the estimation of LLoD and optimal precision (Max 2σ: 2σ at maximum concentration) for chromium analyses under method code XRF-T03. The most reliable estimate of the LLoD and the estimate of the precision of the method was obtained using all 13 of the interval concentration groups, which is illustrated in plots **A** and **B**. Plots **C** and **D** show reference materials greater than 3× LOQ, but not beyond the scope of the method (>3700 ppm) used for calculation of accuracy and bias.

Table 29.1. Summary of figures of merit obtained for XRF-T02 and XRF-T03 methods from duplicate analyses.

	LLoD (ppm)			Precision [a]		
Analyte	**# of Groups**	**Value**	**± 2SD**	**# of Groups**	**Value**	**± 2SD**
XRF-T02 Elements						
As	13	2.35	± 0.25	13	0.3%	± 1.0%
Br	13	0.52	± 0.09	13	2.1%	± 3.6%
Cu	12	0.61	± 0.23	12	1.1%	± 0.07%
Ga	12	0.8	± 0.2	13	1.1%	± 0.91%
Mo	13	0.62	± 0.07	11	0.7%	± 8.3%
Nb	12	0.52	± 0.06	13	1.3%	± 0.58%
Ni	9	1.05	± 0.15	13	0.6%	± 0.09%
Pb	13	1.32	± 0.19	13	1.6%	± 0.47%
Rb	9	0.38	± 0.03	13	1.3%	± 0.11%
Sr	8	0.69	± 0.28	13	0.7%	± 0.10%
Th	13	1.27	± 0.16	12	0.7%	± 3.4%
U	11	0.84	± 0.08	13	4.7%	± 3.5%
Y	13	0.62	± 0.09	13	0.1%	± 0.29%
Zn	11	0.7	± 0.4	13	1.2%	± 0.22%
Zr	8	1.04	± 0.23	13	1.3%	± 0.84%
XRF-T03 Elements						
Ba	6	7.9	± 1.2	13	0.7%	± 0.30%
Ce	9	12	± 1.4	13	1.4%	± 2.0%
Co	9	1.18	± 0.27	13	1.8%	± 0.57%
Cr	13	4.5	± 0.7	13	1.1%	± 0.09%
Cs	13	5.2	± 0.6	13	−3.0%	± 4.9%
La	13	5.8	± 0.6	13	2.8%	± 1.8%
Mn	13	4.8	± 2	13	1.1%	± 0.13%
Sc	12	2.4	± 0.3	9	1.4%	± 2.0%
Ti	11	1	± 4	11	1.3%	± 0.10%
V	13	1.4	± 0.4	13	1.0%	± 0.19%

[a] ***Precision:*** *optimal 2σ precision achievable by the method based on the regression of the reproducibility of duplicate determinations as a function of concentration.*

The LLoDs for analytes were then multiplied by 1.5 and rounded to determine the lower limit of reporting (LLoR) for the methods. The only exception was copper (Cu), because of the presence of tube contamination in the X-ray tube, which was analyzed statistically and determined to produce variation that justified multiplying the LLoD by 3 to provide the new LLoR.

The ULs were estimated using a combination of the calibration and accuracy test set of CRMs. The highest reasonable trace concentration value of either the calibration standards or successfully measured test standard was chosen, with a +10% window for extrapolation (Tables 29.2 and 29.3 provide a summary of the final values).

SUMMARY

The transfer of the XRF-T02 and XRF-T03 methods was a learning process with the new software, but the specialty algorithm modules were intact for the required data processing to produce the calibrations. The evaluation process of the new applications was informative and provided a detailed analysis of the performance of the new methods on the new Zetium® instrument. Based on the analyses used to verify the technique, several conclusions were reached:

Table 29.2. Summary of figures of merit obtained for XRF-T02 method from the analysis of certified reference materials.

	As	Br	Cu	Ga	Mo
Limit of Reporting (LLoR, ppm)	4	0.8	2	1.2	0.9
Limit of Quantification (LoQ, ppm)	13	2.7	7	4.0	3.0
Upper Limit of Validated Range (UL, ppm)	4000	240	6000	125	2000
Relative Standard Deviation (S_r, %)	0.9%	0.6%	0.7%	1.3%	0.7%
Relative Measurement Precision (%)	± 1.8%	± 1.2%	± 1.4%	± 2.6%	± 1.4%
Method Bias (Weighted Regression, %)	4.3%	7.3%	4.7%	2.1%	0.5%
Method Trueness (Mean Absolute Trueness, %)	± 4.4%	± 8.9%	± 4.3%	± 3.4%	± 4.5%

	Nb	Ni	Pb	Rb	Sr
Limit of Reporting (LLoR, ppm)	0.8	1.6	2	0.6	1.0
Limit of Quantification (LoQ, ppm)	2.7	5.3	7	2.0	3.3
Upper Limit of Validated Range (UL, ppm)	1500	6000	4000	3000	4000
Relative Standard Deviation (S_r, %)	1.0%	1.0%	0.7%	0.7%	0.6%
Relative Measurement Precision (%)	± 2%	± 2%	± 1.4%	± 1.4%	± 1.2%
Method Bias (Weighted Regression, %)	4.9%	5.5%	3.6%	1.1%	3.7%
Method Trueness (Mean Absolute Trueness, %)	± 4.1%	± 4.1%	± 3.3%	± 3.2%	± 3.6%

	Th	U	Y	Zn	Zr
Limit of Reporting (LLoR, ppm)	1.9	1.3	0.9	1.1	1.6
Limit of Quantification (LoQ, ppm)	6.3	4.3	3.0	3.7	5.3
Upper Limit of Validated Range (UL, ppm)	220	1600	800	6000	2400
Relative Standard Deviation (S_r, %)	1.4%	0.9%	1.0%	0.6%	0.5%
Relative Measurement Precision (%)	± 2.8%	± 1.8%	± 2%	± 1.2%	± 1%
Method Bias (Weighted Regression, %)	3.8%	1.8%	1.6%	0.7%	2.7%
Method Trueness (Mean Absolute Trueness, %)	± 2.4%	± 3.2%	± 4.2%	± 3.9%	± 2.8%

***Validated Working Range**: Defined as the working range in which the method has been validated (LoQ to maximum concentration used in validation statistics or calibration regression). Minimum and maximum values of reference materials used.*

***Relative Standard Deviation (S_r):** Defined as the average of the relative standard deviations of all measurements greater than 3 × LoQ (Richardson and Morrison 1995).*

***Method Bias (Weighted Regression):** Calculated from the gradient of the linear regression of the measured concentrations against the certified concentrations of the reference materials, with points weighted according to the square root of their variance (Reed 1989, 1990; Richardson and Morrison 1995). Bias = (Gradient − 1) ×100 (result in percent).*

***Method Trueness (Mean Absolute Trueness):** Defined as the average absolute trueness of the suite of reference materials. Only samples with measured concentrations greater than 3× LoQ.*
Absolute Trueness = (|Measured Value − Certified Value|/Certified Value − 1) ×100 (result in percent) (Richardson and Morrison 1995).

- The new methods are accurate over a wide range of concentrations for many elements and yield results that are within accepted published uncertainties for a wide suite of CRMs.
- All figures of merit (LLoD, UL, precision and accuracy) are now confirmed empirically for the total method, including the preparation of samples as pressed pellets with the new binder.
- Greater than 50% of the analytes yielded LLoD results that were improved or the same compared to the previous version of the methods, specifically, As, Br, Cu, Ga, Ni, Rb, Sr, U, Zr, Cr, Mn, Sc and V. These improvements are the consequence of the greater sensitivity of the new instrument, improved overlap corrections and slight dilution (12 g sample with 3 g binder) of the samples with a new binder that improves peak resolution.

Table 29.3. Summary of figures of merit obtained for XRF-T03 method from the analysis of certified reference materials.

	Ba	Ce	Co	Cr	Cs
Limit of Reporting (LLoR, ppm)	12	18	1.8	7	8
Limit of Quantification (LoQ, ppm)	40	60	6.0	23	27
Upper Limit of Validated Range (UL, ppm)	2700	2500	3500	3500	700
Relative Standard Deviation (S_r, %)	1.1%	1.8%	1.1%	0.8%	0.5%
Relative Measurement Precision (%)	± 2.2%	± 3.6%	± 2.2%	± 1.6%	± 1%
Method Bias (Weighted Regression, %)	-1.3%	3.5%	-0.6%	-0.1%	2.8%
Method Trueness (Mean Absolute Trueness, %)	± 4.3%	± 4.2%	± 4.4%	± 4.7%	± 0.7%
	La	**Mn**	**Sc**	**Ti**	**V**
Limit of Reporting (LLoR, ppm)	9	7	4	9	2
Limit of Quantification (LoQ, ppm)	30	23	13	30	7
Upper Limit of Validated Range (UL, ppm)	1500	4000	100	4500	4000
Relative Standard Deviation (S_r, %)	1.4%	0.5%	2.0%	0.4%	1.2%
Relative Measurement Precision (%)	± 2.8%	± 1%	± 4%	± 0.8%	± 2.4%
Method Bias (Weighted Regression, %)	7.9%	5.8%	3.1%	2.2%	1.0%
Method Trueness (Mean Absolute Trueness, %)	± 4.8%	± 3.7%	± 5.5%	± 4.9%	± 3.6%

***Validated Working Range**: Defined as the working range in which the method has been validated (LoQ to maximum concentration used in validation statistics or calibration regression). Minimum and maximum values of reference materials used.*

***Relative Standard Deviation (Sr):** Defined as the average of the relative standard deviations of all measurements greater than 3 × LoQ (Richardson and Morrison 1995).*

***Method Bias (Weighted Regression):** Calculated from the gradient of the linear regression of the measured concentrations against the certified concentrations of the reference materials, with points weighted according to the square root of their variance (Reed 1989, 1990; Richardson and Morrison 1995). Bias = (Gradient − 1) ×100 (result in percent).*

***Method Trueness (Mean Absolute Trueness):** Defined as the average absolute trueness of the suite of reference materials. Only samples with measured concentrations greater than 3× LoQ.*
Absolute Trueness = (|Measured Value − Certified Value|/Certified Value − 1) ×100 (result in percent) (Richardson and Morrison 1995).

- Some of the analytes have slightly degraded LLoDs compared to the previous version of the methods, specifically, Mo, Nb, Pb, Th, Y, Zn, Ba, Ce, Co, Cs and La. The differences seen with these analytes is reasonable because of the new instrumentation and slight dilution with the new binder. Even though 2 instruments may have the same detectors, electrical components and nearly identical geometry, an individual spectrometer is sensitive enough that sensitivity for each analyte can vary between instruments.
- A new, reportable analyte, titanium, was successfully added to XRF-T03. Statistical evaluation of titanium was limited to concentrations between 40 and 5000 ppm Ti. Therefore, there were only 11 groups used to determine the titanium LLoD and the lowest interval mean was 48 ppm Ti, which was well above the calculated LLoD of 1 ± 4 ppm Ti. For more precise estimation of the titanium LLoD, materials with concentration closer to 1 ppm Ti are required.
- Based on the statistical evaluation of the check reference materials, several limitations of the method were identified:
    - Materials containing greater than 2 weight % Mn, 1 weight % Pb, or 1 weight % Zr are inadequately corrected for mass absorption. High concentrations of manganese affect analysis of Mn, Cr, Ce, V, La, Ba, Cs and Sc for such samples. High concentrations of lead will affect all analytes except Mo, Nb and Th. High concentrations of zirconium will affect the analysis of all analytes in XRF-T02 and XRF-T03.

- Analytes Nb, Zr, Th, U, and Y are inadequately corrected for strontium concentrations higher than 7500 ppm Sr. Samples that contain large amounts of strontium yield biased values for these analytes.
- Analytes Ce and La are inadequately corrected for high concentrations (>5000 ppm) of Mn, Cr, V and Nd. Preparation of synthetic materials may resolve this issue.
- There is a lack of suitably prepared (suitable grain size, tolerable mineralogical effects), well-characterized or well-constrained reference materials to choose from for refining calibrations (overlaps, concentrations), statistical evaluation and checks for some of the analytes. This is particularly evident for As, Br, Ce, Cs, La, Sc and U.

The XRF-T02 and XRF-T03 methods are as robust on the new instruments as the previous versions were and are fit for purpose. As time and resources permit, improvements or enhancements will be implemented, and evaluation of the methods revisited.

ACKNOWLEDGMENTS

The pandemic situation in 2020 was a major influence on the receipt and installation of the new spectrometers. I would like to thank John Beals for ensuring that the replacement of the spectrometers continued to move forward and Rick DeBres of Malvern Panalytical® for the extra work and quick response necessary to bring the new spectrometer online as quickly as possible. Their contribution to the spectrometer replacement allowed me to transfer our methods as quickly as possible, all things considered.

REFERENCES

PANalytical 2006. PANalytical SuperQ 5.0 manual; PANalytical B.V., Almelo, Netherlands.

Reed, B.C. 1989. Linear least-squares fits with errors in both coordinates; American Journal of Physics, v.57, p.642-646.

——— 1990. Erratum “Linear least-squares fits with errors in both coordinates”; American Journal of Physics, v.58, p.189.

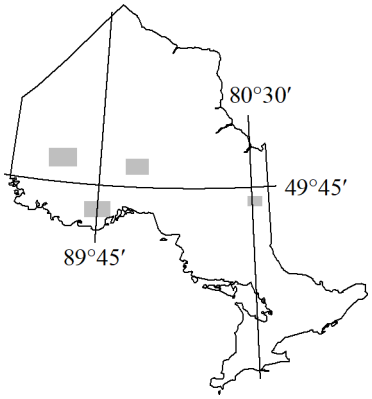
Richardson, J.M. and Morrison, J.L. 1995. Method validation in the Ontario Geoscience Laboratories; Analyst, v.120, p.1519-1526.

Thompson, M. and Howarth, R.J. 1976. Duplicate analysis in geochemical practice. Part I. Theoretical approach and estimation of analytical reproducibility; Analyst, v.101, p.690-698.

Willis, J.P. and Duncan, A.R. 2008. Understanding XRF spectrometry, volume I: Basic concepts and instrumentation; PANalytical B.V., Almelo, Netherlands.

Resident Geologist Program

30. Identification of Fertile Parent Granitoid Units in the Superior Province of Ontario: Project Description



R.M. Cundari[1]

[1]Resident Geologist Program, Ontario Geological Survey

INTRODUCTION

Peraluminous granites are widely distributed throughout the Superior Province of Ontario, most notably within and adjacent to the metasedimentary rocks of the English River and Quetico subprovinces from which they derived by partial melting. There has been a significant amount of work that proposes a direct genetic relationship between peraluminous, S-type granitoids (i.e., fertile parent granites) and rare-element pegmatites of the lithium-cesium-tantalum (LCT) group (enriched in Li, Cs, Rb, Tl, Be, Ta, Nb, Ga and Ge) across the world (*see* for instance Černý 1989, 1991; Wise, Müller and Simmons 2022, and references therein) and in the Superior Province (Breaks, Selway and Tindle 2003; Selway, Breaks and Tindle 2006). Breaks, Selway and Tindle (2003, p.1) stated:

> Recognition of peraluminous granites is critical in the exploration for rare-element pegmatites because delineation of such granite masses effectively reduces the target area of investigation. Most pegmatite swarms that can be linked with an exposed fertile, parent granite pluton are situated within approximately 15 km of such granites (e.g., Separation Rapids pluton and eastern and southwestern rare-element pegmatite groups: Breaks and Tindle, 1996, 1997a, 1997b).

The intent of the fertile granite project is to identify previously unrecognized fertile parent granitoids in the Superior Province of Ontario to assist in the discovery of LCT group pegmatite fields. This article provides background information on the importance of locating fertile parent granitoid bodies, the scope of the project being led by the Resident Geologist Program (RGP) and an overview of progress made during the 2022 field season.

SCOPE

A fertile granite is the parental granite to rare-element pegmatite intrusions. Many granitic melts have the capability to generate fertile granite plutons that will, in turn, produce even more fractionated melts enriched in incompatible elements. In the case of the LCT group pegmatite, the residual melt may percolate into the surrounding host rock and crystallize rare-element pegmatites (Breaks, Selway and Tindle 2003). Identifying fertile parent granites is an important step in the exploration for rare-element pegmatites as it greatly reduces the search area on a regional scale (Breaks and Tindle 1997a).
A significant amount of work was performed by the Ontario Geological Survey (OGS) in the late 1990s and early 2000s to improve our understanding of rare-element pegmatites and their parent granitoid units in the Superior Province, with a focus on northwestern Ontario (e.g., Breaks, Selway and Tindle 2003). The areas covered by the aforementioned studies targeted specific areas in subprovinces and many of the tectonic lithospheric scale boundaries between these subprovinces; they are listed as follows:

Summary of Field Work and Other Activities, 2022,
Ontario Geological Survey, Open File Report 6390, p.30-1 to 30-5.

© King's Printer for Ontario, 2022

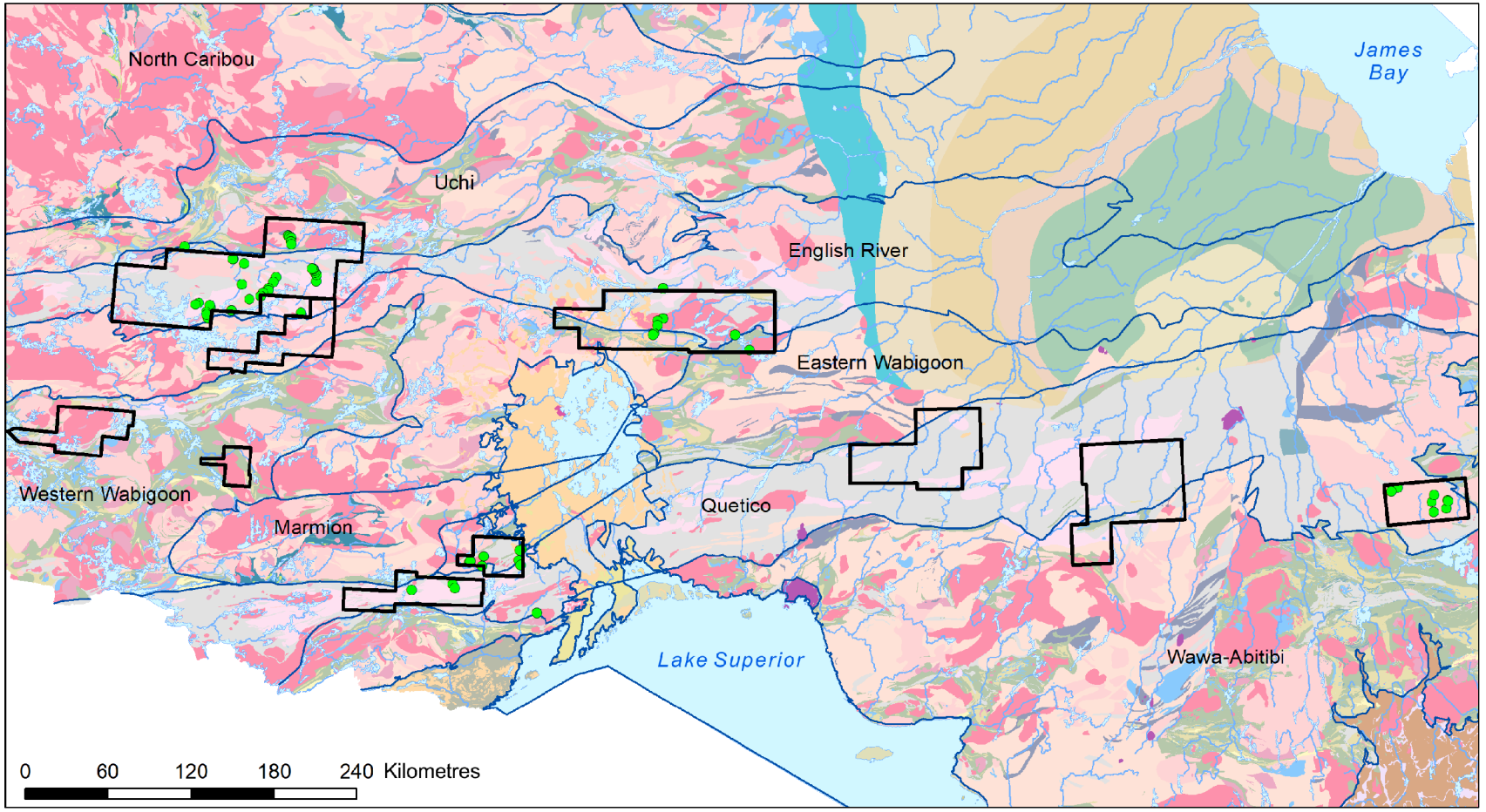


Figure 30.1. Locations of fertile granite project target areas (outlined in black) and sample locations (green dots) to date. Regional geology *from* Ontario Geological Survey (2011, see publication for a detailed geological legend). Subprovince boundaries are based on Stott (2011) and are outlined in blue. These boundaries are shown extending beneath Phanerozoic cover rocks in the James Bay area.

the Wabigoon–English River subprovinces boundary near Armstrong, the Quetico Subprovince near Hearst, the Quetico–Wabigoon subprovinces boundary near Pagwachuan, the Opatica Subprovince near Lake Abitibi (Breaks, Selway and Tindle 2006), and a detailed study of the Georgia Lake pegmatite field (Breaks, Selway and Tindle 2008; Tindle, Breaks and Selway 2008).

This project aims to investigate areas of the Superior Province that were not examined by the aforementioned OGS studies in order to provide a comprehensive overview of the geology and geochemistry of fertile granitoid units in the Superior Province. The study will focus mainly on new areas within the Quetico and English River subprovinces, because they are the most suitable geological domains to host peraluminous granitoid rocks. Attention will also be given to localized areas within the Wabigoon Subprovince proximal to previously identified pegmatite fields to better characterize the linkage between known pegmatites and their fertile parents. The project will primarily use whole-rock geochemical data to determine the fertility of potential fertile granite units. Additionally, mineral chemistry (potassium feldspar, muscovite and spessartine-rich garnet) will be performed with the electron probe microanalyzer (EPMA) at the Geoscience Laboratories (Sudbury) to further characterize units and fractionation patterns that show favourable geochemical characteristics and economic potential. The key goal of the fertile granites project is to assist the mineral exploration industry in identifying new areas potentially hosting LCT group pegmatites.

PRELIMINARY WORK

Ten areas of the Superior Province in Ontario have been identified for study as part of the fertile granite project (Figure 30.1). Locations for sampling were selected to complement the existing granitoid geochemical databases acquired by the OGS and published in Miscellaneous Release—Data (MRD) 111 (Tindle, Selway and Breaks 2002), MRD 210 (Tindle, Selway and Breaks 2006) and MRD 231 (Tindle, Breaks and Selway 2008), as well as to provide coverage in areas previously not investigated for the presence of fertile granitoid rocks and associated LCT group pegmatites. The 2022 field season was intended as a preliminary investigation of the selected areas. A total of 100 samples were collected and will be analyzed for both major, trace element and rare earth element geochemistry at the Geoscience Laboratories (Sudbury) to identify potential fertile parent granite bodies (*see* Figure 30.1).

Barren granites generally contain biotite and/or muscovite as their minor minerals, and apatite, zircon and titanite as accessory minerals (Breaks and Tindle 1997a). Fertile granites contain muscovite as a minor mineral phase, along with a wide variety of accessory phases, including primary green lithium-bearing muscovite, garnet, tourmaline, apatite, cordierite and rarely andalusite and topaz (Černý 1989; Breaks and Tindle 1997a). More evolved fertile granites contain beryl, ferrocolumbite (niobium-oxide mineral) and lithium-rich tourmaline (Breaks and Tindle 1997a). The majority of samples collected in the summer of 2022 are from granites that contained muscovite as a minor mineral phase and were devoid of biotite. In select locations, samples also contained garnet, apatite, tourmaline and beryl as accessory mineral phases. Petrographic work and X-ray diffraction (XRD) analyses will be implemented to confirm the presence of these accessory minerals in selected samples. Geochemical analyses performed at the Geoscience Laboratories (Sudbury) of these samples are still pending at the time of publication.

FUTURE WORK

Further work in support of the fertile granite project will include preliminary evaluation of the geochemical data set generated during the summer of 2022, compilation of geochemical data from previous studies and planning for additional sampling during the 2023 field season. Collation and interpretation of data is intended to take place in the fall–winter of 2023. The primary deliverable of the project will be an MRD compiling previously released whole-rock geochemical data related to fertile

granites (i.e., Tindle, Selway and Breaks 2002, 2006; Tindle, Breaks and Selway 2008). This compilation will be supplemented with the new whole-rock geochemical data acquired during this study. Interpretation and discussion of the data generated from the project will be released as either a compendium to the MRD, or as a separate Open File Report. Additionally, several articles will potentially be generated and released during the course of the project in both the Resident Geologist Program *Recommendations for Exploration* (released annually in January) and the *Report of Activities* (published annually in the spring).

ACKNOWLEDGMENTS

The Fertile Granites project is a collective effort with team members from across the Resident Geologist Program conducting field work in support of this project (Ethan Amyotte, Zeinab Azadbakht, Peter Chadwick, Sophie Kurucz, Justin Jonsson, Paul Malegus, Greg Paju, Therese Pettigrew). Mark Puumala, Manuel Duguet and Michael Easton are thanked for technical guidance and for editing of this article. Dawn-Ann Metsaranta is also thanked for her technical guidance and administrative support toward this project. Mathieu Levesque and Darla Bennett contributed to recognizing sensitivities related to First Nation land claims in the province. Alexandra Withers, Marcus Burnham and Victoria Hingst from Geoscience Laboratories provided guidance and support related to analytical methods.

REFERENCES

Breaks, F.W., Selway, J.B. and Tindle, A.G. 2003. Fertile peraluminous granites and related rare-element mineralization in pegmatites, Superior Province, northwest and northeast Ontario: Operation Treasure Hunt; Ontario Geological Survey, Open File Report 6099, 179p.

——— 2006. Fertile and peraluminous granites and related rare element mineralization in pegmatites, north-central and northeastern Superior Province, Ontario; Ontario Geological Survey, Open File Report 6195, 143p.

——— 2008. The Georgia Lake rare-element pegmatite field and related S-type, peraluminous granites, Quetico Subprovince, north-central Ontario; Ontario Geological Survey, Open File Report 6199, 176p.

Breaks, F.W. and Tindle, A.G. 1996. New discovery of rare-element pegmatite mineralization, Separation Lake area, northwestern Ontario; Ontario Geological Survey, Open File Report 5946, 9p.

——— 1997a. Rare-element exploration potential of the Separation Lake area: An emerging target for Bikita-type mineralization in the Superior Province of northwest Ontario; *in* Summary of Field Work and Other Activities, 1997, Ontario Geological Survey, Miscellaneous Paper 168, p.72-88.

——— 1997b. Rare-element exploration potential of the Separation Lake area: An emerging target for Bikita-type mineralization in the Superior Province of northwest Ontario; Ontario Geological Survey, Open File Report 5966, 27p.

Černý, P. 1989. Exploration strategy and methods for pegmatite deposits of tantalum; *in* Lanthanides, tantalum and niobium, Springer-Verlag, New York, p.274-302.

——— 1991. Rare-element granitic pegmatites. Part 1: Anatomy and internal evolution of pegmatite deposits. Part 2: Regional to global environments and petrogenesis; Geoscience Canada, v.18, p.49-81.

Ontario Geological Survey 2011. 1:250 000 scale bedrock of Ontario; Ontario Geological Survey, Miscellaneous Release—Data 126 – Revision 1.

Selway, J.B., Breaks, R.W. and Tindle, A.G. 2006. A review of rare-element (Li-Cs-Ta) pegmatite exploration techniques for the Superior Province, Canada, and large worldwide tantalum deposits; Exploration and Mining Geology, v.14, no.1-4, p.1-30.

Stott, G.M. 2011. A revised terrane subdivision of the Superior Province in Ontario; Ontario Geological Survey, Miscellaneous Release—Data 278.

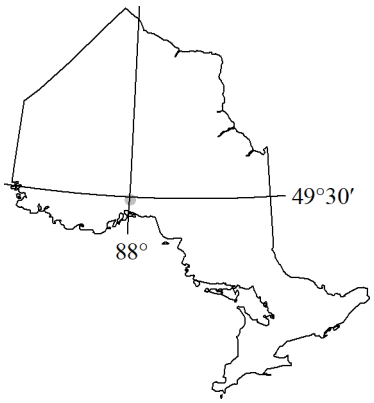
Tindle, A.G., Breaks, F.W. and Selway, J.B. 2008. Electron microprobe and bulk rock and mineral compositions from S-type, peraluminous granitic rocks and rare-element pegmatites, Georgia Lake pegmatite field, Quetico Subprovince, north-central Superior Province of Ontario; Ontario Geological Survey, Miscellaneous Release—Data 231.

Tindle, A.G., Selway, J.B. and Breaks, F.W. 2002. Electron microprobe and bulk analyses of fertile peraluminous granites and related rare-element pegmatites, Superior Province, northwest and northeast Ontario: Operation Treasure Hunt; Ontario Geological Survey, Miscellaneous Release—Data 111.

——— 2006. Electron microprobe and bulk rock and mineral compositions of barren and fertile peraluminous granitic rocks and rare-element pegmatites, north-central and northeastern Superior Province of Ontario; Ontario Geological Survey, Miscellaneous Release—Data 210.

Wise, M.A., Müller, A. and Simmons, W.B. 2022. A proposed new mineralogical classification system for granitic pegmatites; The Canadian Mineralogist, v.60, p.229-248. doi.org/10.3749/canmin.1800006

31. Investigation of Biogeochemical Exploration Techniques to Aid in the Exploration for Lithium-Cesium-Tantalum Pegmatite Dikes: Project Description and Preliminary Observations



E.G. Amyotte[1], S.V. Kurucz[1], G.F. Paju[1], J.R.B. Jonsson[1] and C.E. Kurcinka[1]

[1]Resident Geologist Program, Ontario Geological Survey

INTRODUCTION

The intent of this pilot survey is to refine methods for using biogeochemical techniques as an exploration tool for exploration of lithium-cesium-tantalum (LCT) pegmatites (classification of Černý 1982). This survey collected vegetation and rock samples over 2 LCT pegmatites and their metasedimentary host rocks to determine if inductively coupled plasma mass spectrometry (ICP–MS) trace element analyses of the vegetation samples could be used to interpret the presence of the buried rock types. A total of 119 samples from black spruce, grey alder and humus were collected in the Georgia Lake area by the Resident Geologist Program between July 5 and 7, 2022. The sampling locations were the Georgia Lake lithium property (held by Rock Tech Lithium Inc.) and the Jackpot property (held by Imagine Lithium Inc.) (Figure 31.1).

REGIONAL AND PROPERTY GEOLOGY

The study area is underlain by rocks of the Quetico Subprovince of the Superior Province, an approximately east-trending belt with a width of approximately 70 km and a length of more than 1000 km, stretching from Minnesota, through Ontario and into Quebec (Williams 1991; Stott et al. 2010). It is a predominantly metamorphosed sedimentary subprovince with abundant granite and pegmatite intrusions that are derived primarily from anatexis of the sedimentary rocks (Card and Ciesielski 1986; Percival and Sullivan 1988).

Metasedimentary rocks of the Quetico Subprovince are an ideal source for peraluminous S-type granites, such as the Glacier Lake batholith, which is interpreted to be the parental fertile granitic body from which the Georgia Lake pegmatite field was generated (Breaks, Selway and Tindle 2008; Duguet 2019) (*see* Figure 31.1). Peraluminous and pegmatitic granitic bodies of the Glacier Lake batholith crop out over an area of 40 km by greater than 110 km. The Georgia Lake pegmatite field represents the largest known concentration of rare earth metal mineralization within the Quetico Subprovince (Breaks, Selway and Tindle 2008).

The Georgia Lake lithium property, held by Rock Tech Lithium Inc., encompasses the Postagoni Lake pegmatite group that was described by Breaks, Selway and Tindle (2008) (*see* Figure 31.1) and which was identified as one of 6 distinct pegmatite groups in the area. The geology of the property includes

Summary of Field Work and Other Activities, 2022,
Ontario Geological Survey, Open File Report 6390, p.31-1 to 31-7.

© King's Printer for Ontario, 2022

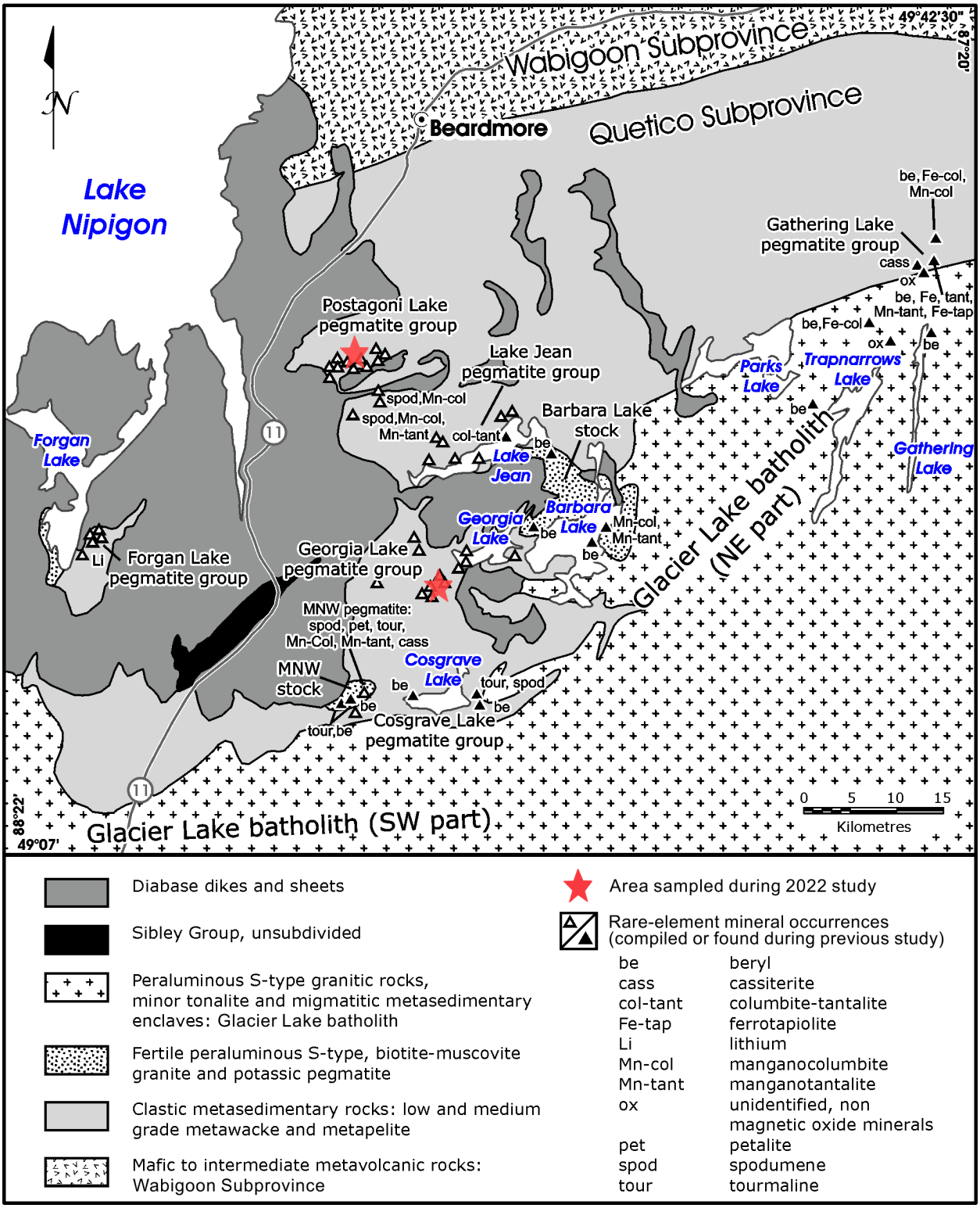


Figure 31.1. General geological setting of rare-element pegmatites of the Georgia Lake field and adjacent granitic rocks of the Glacier Lake batholith (*modified from* Breaks, Selway and Tindle 2008). The 2 study areas sampled during this project are marked by the red stars. The locations of rare-element mineral occurrences (as of 2008) are indicated by filled or unfilled triangles found or compiled, respectively, during the study by Breaks, Selway and Tindle (2008).

the targeted pegmatites along with the surrounding metasedimentary and granitic bedrock of the Quetico Subprovince. Granitic intrusions in the Georgia Lake property are associated with genetically related aplite, pegmatites and porphyries (Pye 1965). Pegmatites are common near granitic bodies as well as within larger granitic masses, and they are interpreted to be genetically related to the granites (Breaks, Selway and Tindle 2008; Duguet 2019). The pegmatites contain rare earth metal mineralization and are composed of feldspar, quartz, muscovite and spodumene with minor amounts of beryl, columbite-tantalite and cassiterite (Pye 1965). Rock Tech Lithium Inc. refers to the area sampled by this study as the northwestern portion of the "North Spodumene Pegmatite Area". A NI 43-101-compliant Preliminary Economic Assessment published in 2021 outlines a Measured and Indicated Mineral Resource of 6.62 Mt at 1.01% Li_2O and an Inferred Mineral Resource of 6.68 Mt at 1.16% Li_2O (Hanrahan et al. 2021, p.28).

The Jackpot property, held by Imagine Lithium Inc., is located in the Georgia Lake pegmatite group of the Georgia Lake pegmatite field (Breaks, Selway and Tindle 2008) (*see* Figure 31.1). The distribution of rock types at the Jackpot property is similar to the Rock Tech Lithium Inc. property, encompassing Archean metasedimentary rocks, granite and granitic pegmatites, as well as Mesoproterozoic Nipigon diabase sills (historical Keweenawan sills). East- to northeast-trending, steeply north-dipping metasedimentary rocks (quartz-mica schist and gneiss) underlie most of the Jackpot property (Gilmour 1955). Granitic intrusions, composed of microcline, albite, and quartz ± biotite and muscovite, occur throughout the property, including the northern extent of the Glacier Lake batholith located on the southern edge of the property (Pye 1965; Weicker 2020). Pegmatite dikes on the Jackpot property intruded metasedimentary host rocks and are composed primarily of quartz, white feldspar and pale green spodumene, along with minor muscovite and accessory apatite, beryl and tourmaline (Gilmour 1955; Pye 1965). The area visited during this study is known as the "Main Zone", hosting the "No. 1" and "No. 2" pegmatites. The "No. 1" pegmatite strikes approximately 65°, crops out at surface with thicknesses of 6 to 9 m, and is interpreted to be the erosional remnant of a flat-lying sheet. It is underlain by the "No. 2" pegmatite, an approximately 11 m thick dike striking approximately 65° and dipping 15 to 25° to the northwest (Wiecker 2020). The "No. 2" dike constitutes the property's non-NI 43-101-compliant historical resource of 1.814 Mt at 1.09% Li_2O, calculated in 1956 by the Ontario Lithium Company (Pye 1965).

BIOCHEMICAL PROJECT SAMPLING

The Georgia Lake lithium (Figure 31.2) and Jackpot properties (Figure 31.3) were selected based on their geological continuity, mineralogy, vegetation availability and accessibility. Spodumene pegmatites were selected as currently their mineralogy is best suited to meet the lithium demands of the critical minerals market and, in addition, have high exploration potential in Ontario. At each property, 2 sample lines were used perpendicular to the strike of the pegmatite. Sample locations along the lines were selected to capture samples that would be representative of the underlying rock types, and where vegetation of a relatively consistent age and size was best available for sampling. At each locality, barring sampling limitations, 5 samples were collected, including outer bark and twig ends (including needles) of *Picea mariana* (black spruce); leaves and twigs of *Alnus incana* (grey alder); and a rock sample from outcrop. A single black spruce tree top and a single humus sample were also collected.

Black spruce and grey alder were chosen because these are common vegetation types in northwest Ontario, were readily available over the target areas, and both have been demonstrated to take up pathfinder elements associated with LCT pegmatites (Fedikow et al. 2017; Pedersen 2017). Vegetation media chosen for collection took into account sampling practicality, and samples (>50 g) were collected for each sample medium. For black spruce, this included outer bark and twig ends (up to 5 branch nodes from the end of a twig) and needles, all of which were collected in plastic sample bags. Outer bark was sampled by hand peeling or scraping using a plastic scraper where necessary. For grey alder, leaves and twigs were collected separately in cloth sample bags. Leaves were hand picked, and twigs were sampled up to 3 nodes into the tree. At one site, a single treetop was collected as the black spruce tree had partly

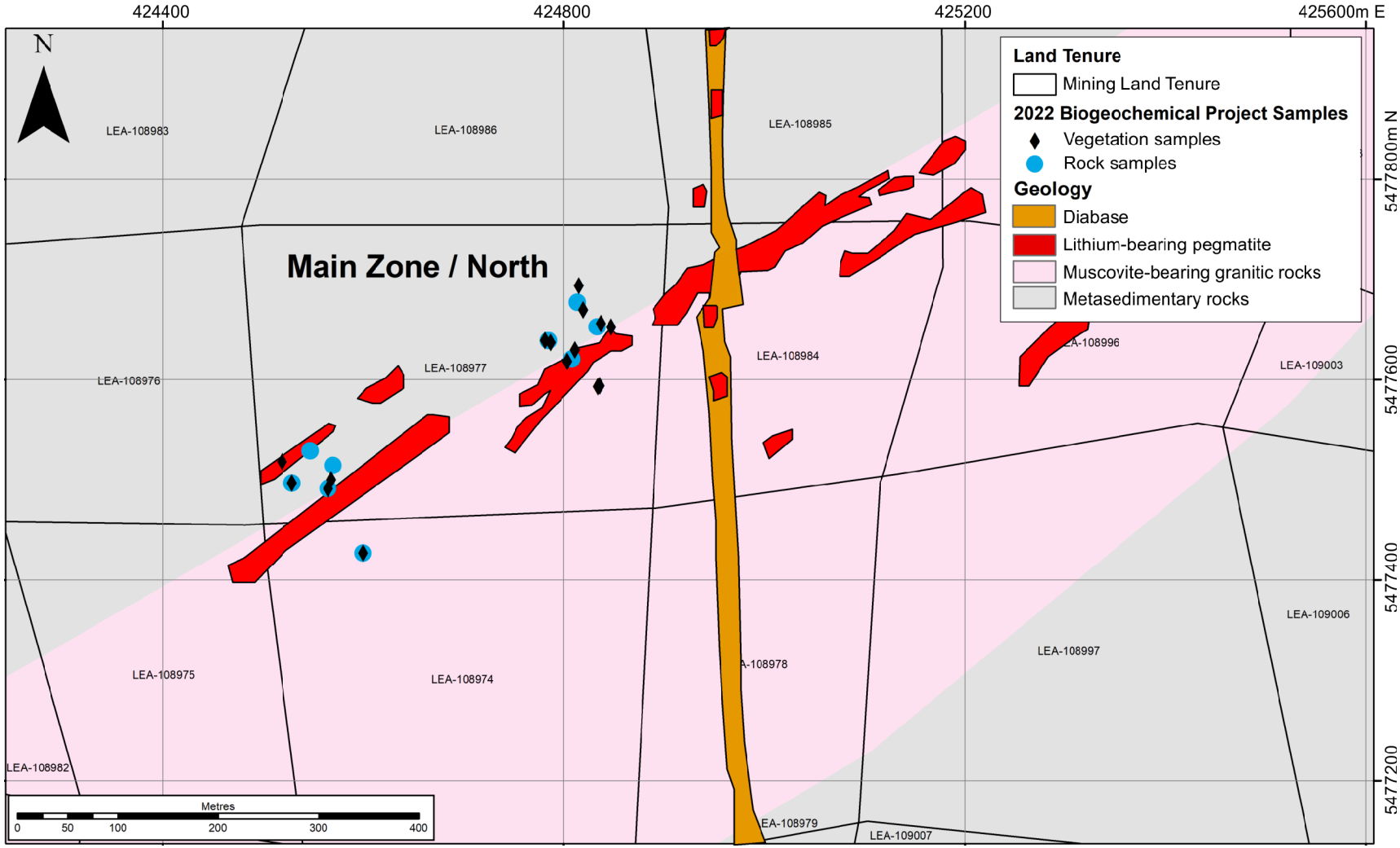


Figure 31.2. Simplified geology of the Rock Tech Lithium Inc. Georgia Lake lithium property showing bedrock geology overlain by pegmatite dikes (red) and showing the locations of 2022 biogeochemical project samples (black-filled diamonds and blue dots). Bedrock geology *modified from* Ontario Geological Survey (2011); locations of pegmatite dikes *modified from* Selway et al. (2011, p.108).

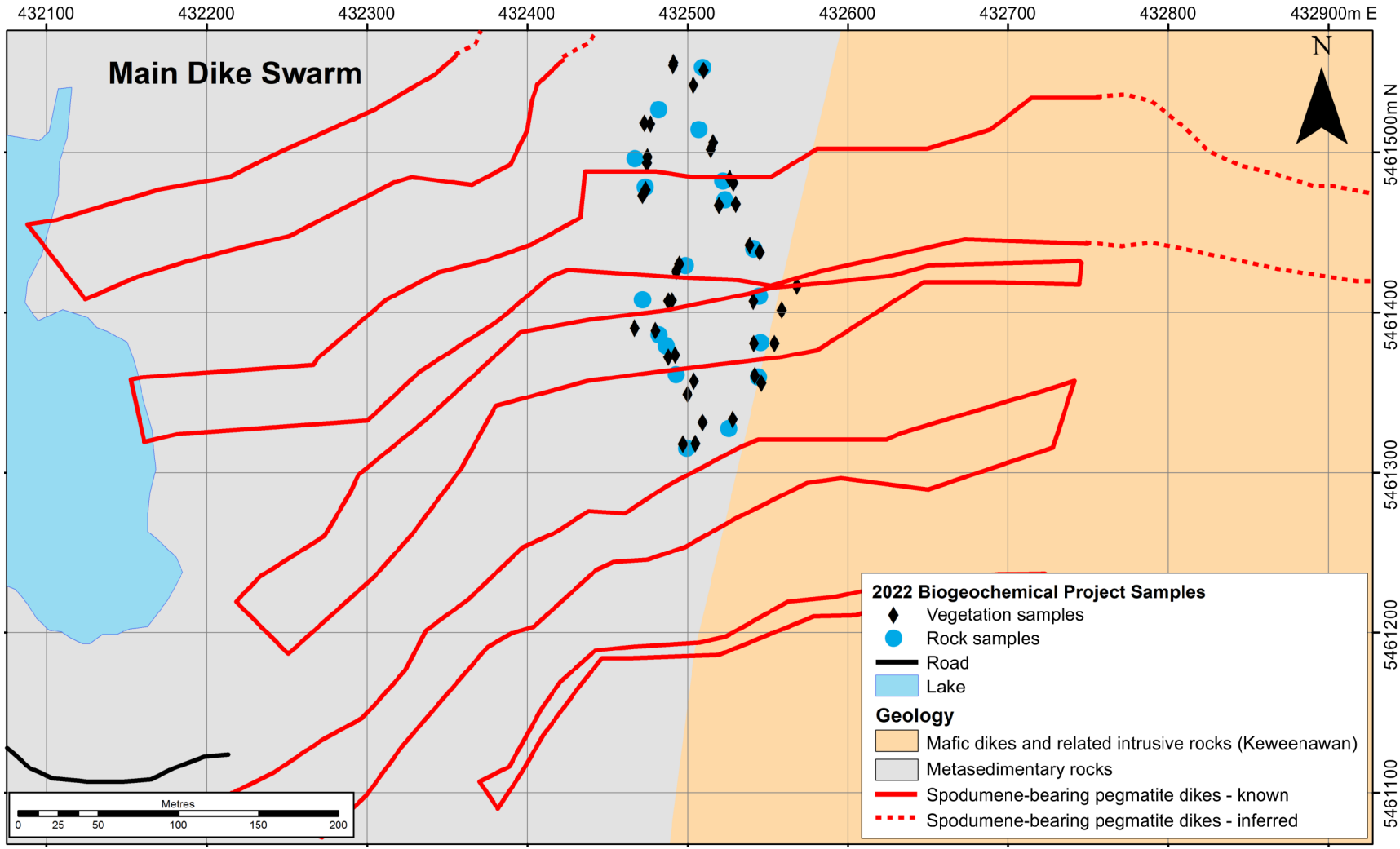


Figure 31.3. Simplified geology of the Imagine Lithium Inc. Jackpot property showing bedrock geology overlain by pegmatite dikes (red outlines) and showing the locations of 2022 biogeochemical project samples (black-filled diamonds and blue dots). Bedrock geology *modified from* Ontario Geological Survey (2011); locations of known and inferred pegmatite dikes *modified from* Imagine Lithium Inc. (Imagine Lithium Inc., news release, March 21, 2022).

fallen over and was accessible. A single humus sample was collected over the spodumene pegmatite itself for comparison with other sample media. Following sampling, vegetation samples were dried, milled and ashed at 485°C prior to mixed acid digestion and ICP–MS analysis for the range of trace elements commonly analyzed in rocks, including the rare earth elements (REE), high field strength elements (HFSE, in particular Nb, Ta), and large-ion lithophile elements (LILE, including Li, Be, Rb, Sr, Cs and Ba).

A total of 119 vegetation samples and 21 rock samples were collected during the 2022 sampling program. At the Georgia Lake lithium property (*see* Figure 31.2), 25 samples were collected. At the Jackpot property, 61 samples were collected (*see* Figure 31.3), consisting of 7 sample locations per line where 2 to 3 samples were collected over each rock type. Because of sampling limitations at the Georgia Lake property, the 2 sample lines consisted of 5 sample locations, of which 3 locations were on the metasedimentary host rock and 2 were sampled atop the pegmatite. Along the southwestern sample line, alder leaves could not be collected as caterpillars had eaten the leafy vegetation. Analytical work is being conducted at the OGS Geoscience Laboratories in Sudbury. Laboratory results are pending at the time of publication.

FUTURE WORK

Continued work for this project will include reviewing and interpreting the laboratory data after completion of the analyses, with an emphasis on determining if biogeochemical sampling can be used to aid in the exploration of LCT pegmatites. Depending on the 2022 program results, future work may include resampling of the Jackpot property locations earlier in the field season to compare the effect of seasonal variations on vegetation chemistry, and sampling over a LCT pegmatite outside of the Georgia Lake area and with different mineralogy. Exploring a variety of geological settings and vegetation characteristics will aid in the project's goal of providing a standardized method for LCT pegmatite biogeochemical sampling, as has been established for other mineral deposit types, such as for gold and platinum group elements.

ACKNOWLEDGMENTS

Marcus Burnham, Geoscience Laboratories, is recognized for his mentorship and for the development an analytical methodology for the analysis of the vegetation samples. Sergio Bautista provided sampling assistance and good conversation during the long travel days. Paul Malegus, Red Lake Resident Geologist, is thanked for help in the conceptualization of this project. Mark Puumala and Rob Cundari. Resident Geologist Program, provided invaluable feedback when considering target areas for sampling. Michael Easton and Manuel Duguet, Earth Resources and Geoscience Mapping Section, are thanked for their thorough review of the publication.

REFERENCES

Breaks, F.W., Selway, J.B. and Tindle, A.G. 2008. The Georgia Lake rare-element pegmatite field and related S-type, peraluminous granites, Quetico Subprovince, north-central Ontario; Ontario Geological Survey, Open File Report 6199, 176p.

Card, K.D. and Ciesielski, A. 1986. Subdivisions of the Superior Province of the Canadian Shield; Geoscience Canada, v.13, p.5-13.

Černý, P. 1982. Anatomy and classification of granitic pegmatites; *in* Granitic pegmatites in science and industry, Mineralogical Association of Canada, Short Course Handbook 8, p.1-39.

Duguet, M. 2019. Archean and Proterozoic geology of the Georgia Lake area, Quetico Subprovince, Ontario; *in* Summary of Field Work and Other Activities, 2019, Ontario Geological Survey, Open File Report 6360, p.12-1 to 12-10.

Fedikow, M.A.F., Dunn, C.E., Martins, T. and Lee, S.K.Y. 2017. Biogeochemistry data from a vegetation orientation survey in the area of the Tanco pegmatite, Bernic Lake, southeastern Manitoba (NTS 52L6); Manitoba Geological Survey, Data Repository Item DRI2017001, Microsoft® Excel® file, www.gov.mb.ca/iem/info/library/downloads/mineral_resources.html [accessed October 9, 2022].

Gilmour, P. 1955. Geological report, Ontario Lithium Company Limited, Georgia Lake property; unpublished report, Thunder Bay Resident Geologist's office, assessment file AFRO# 63A.309 AFRI# 42E05SW0026, 29p.

Hanrahan, R.J., Larder, C., Peters, K.S., Lowicki, F., Puritch, E., Feasby, D.G. and Kuchling, K. 2021. Preliminary economic assessment for an integrated lithium hydroxide operation from the Georgia Lake lithium project, northwest Ontario, Canada, prepared for Rock Tech Lithium Inc. by Wave International Pty Ltd, DMT GmbH & Co. KG, and P&E Mining Consultants Inc., March 15, 2021; Technical Report, NI 43-101 filed April 21, 2021 with SEDAR®, *see* SEDAR Home Page, 241p.

Ontario Geological Survey 2011. 1:250 000 scale bedrock geology of Ontario; Ontario Geological Survey, Miscellaneous Release—Data 126 – Revision 1.

Pedersen, J.C. 2017. Assessment report for summer 2017 field work on the Paterson Lake claims, Paterson Lake area, Separation Rapids, Ontario, prepared for Avalon Advanced Materials; unpublished report, Thunder Bay Resident Geologist's office, assessment file AFRO# 2.58249, AFRI# 20000015331, 179p.

Percival, J.A. and Sullivan, R.W. 1988. Age constraints on the origin of the Quetico belt, Superior Province, Canada; *in* Radiogenic and Isotope Studies: Report 2, Geological Survey of Canada, Paper 88-2, p.97-107.

Pye, E.G. 1965. Georgia Lake area; Ontario Department of Mines, Report 31, 113p.

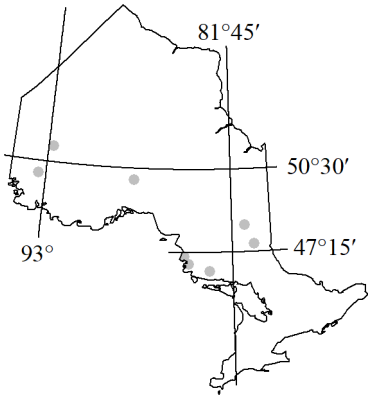
Selway, J.B., Baker, J.A., Peshkepia, A., Magyarosi, Z. and Dixon, A. 2011. Independent technical report and estimated resources for Georgia Lake lithium property, Beardmore, Ontario, Canada, prepared for Rock Tech Lithium Inc. by Caracle Creek International Consulting Inc.; NI 43-101 Technical Report, filed November 3, 2011 with SEDAR®, *see* SEDAR Home Page, 328p.

Stott, G.M., Corkery, M.T., Percival, J.A., Simard, M. and Goutier, J. 2010. A revised terrane subdivision of the Superior Province; *in* Summary of Field Work and Other Activities, 2010, Ontario Geological Survey, Open File Report 6260, p.20-1 to 20-10.

Wiecker, R.F. 2020. Assessment report on diamond drill program on the Jackpot property, Thunder Bay Mining Division, Barbara Lake Township, Infinite Ore Corp; unpublished report, Thunder Bay Resident Geologist's office, assessment file AFRI# 20000018558, 209p.

Williams, H.R. 1991. Quetico Subprovince; Chapter 10 *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, p.383-403.

32. Catching it by the Tailings: An Introduction to the Ontario Geological Survey Critical Minerals Mine Waste Sampling Project



D.J. Bennett[1,2]

[1]Resident Geologist Program Section, Ontario Geological Survey
[2]Director's Office, Ontario Geological Survey

INTRODUCTION

Critical minerals are minerals that meet 2 criteria: first, they are needed to support specific industrial, technological or strategic applications, and second, they have few or no viable alternatives and are at risk for supply chain disruptions (International Energy Agency 2022). They are also needed to move toward a green economy and to reduce net carbon emissions. Many sources of critical minerals are difficult to access and to process, and can have associated environmental challenges[3]. Recent advancements in recovery and refinement techniques may alleviate some of these challenges; however, there is a more immediate opportunity to explore potential sources for critical minerals within Ontario's historic mine waste sites. Some critical minerals are associated with historically mined minerals, but because those critical minerals were not economically viable or desirable at the time, they were left within the waste (*Global Mining Review*, May 27, 2022, www.globalminingreview.com/mining/27052022/a-critically-wasted-opportunity[4]). Additionally, economically viable concentrations for certain minerals have changed over time as high-grade resources have become depleted, resulting in the potential for waste rock to be reprocessed, whether for minerals or building materials (*Global Mining Review*, May 27, 2022, www.globalminingreview.com/mining/27052022/a-critically-wasted-opportunity). To assist in the exploration and testing aspect of potentially viable mine waste sites, the mine waste sampling project was created by the Ontario Geological Survey (OGS) in 2021 (Azadbakht et al. 2022, p.52-54). The project aims to identify sites where residual critical minerals may be present and available for potential reprocessing. The project targets both Crown land and privately held land. Viable sites may have an advantage in having some infrastructure already present, thereby reducing processing time and procedures compared to finding and extracting from a new resource.

PHASE 1: PILOT STUDY SITES

Initiated by the Resident Geologist Program (RGP) in 2021, a small pilot study termed "phase 1", was carried out on 2 abandoned mine sites (Figure 32.1). The pilot sites have allowed a better understanding of the mineralogy of the tailings, the potential secondary commodities still present in the

[3] *Information related to the Ontario critical minerals list is available at Critical minerals | ontario.ca and Ontario's Critical Mineral Strategy 2022–2027 is available for download at Ontario's Critical Minerals Strategy 2022–2027: Unlocking potential to drive economic recovery and prosperity | ontario.ca.*

[4] *The author notes that Web addresses were accessed on November 18, 2022.*

Summary of Field Work and Other Activities, 2022,
Ontario Geological Survey, Open File Report 6390, p.32-1 to 32-6.

© King's Printer for Ontario, 2022

waste, the types of analysis that will best serve the project objectives and has helped to develop a sampling protocol. The phase 1 pilot study included the Langmuir Mine, in Langmuir Township, near Timmins (Abandoned Mine Identifier 10069; MDI42A06SE00006) and the Coppercorp Mine in Ryan Township, near Sault Ste. Marie (Abandoned Mine Identifier 08061; MDI41N02SW00004). (Abandoned Mine Identifier data *from* Mines and Minerals Division 2022; MDI data *from* Ontario Geological Survey 2022.) These 2 sites were chosen because of their accessibility, location, and potential stores of nickel and copper, respectively (as well as any other critical minerals that may also remain in the tailings); both sites were sampled in November 2021.

The Langmuir Mine was in production from 1976 to 1992 and produced more than 100 000 t of ore grading 2.2% Ni during operations (*Canadian Mining Journal*, May 21, 2014, www.canadianminingjournal.com/news/nickel-inspiration-to-dewater-former-langmuir-mine). More recent drilling by Inspiration Mining Corp. shows that there is a potential for low-grade, high-tonnage nickel production (*Canadian Mining Journal*, May 21, 2014, www.canadianminingjournal.com/news/nickel-inspiration-to-dewater-former-langmuir-mine). The site itself is quite large, with both a large tailings pond and a smaller dewatering pond. The site size limited initial sampling because of the amount of equipment and sample weight and, therefore, the quantity and diversity of samples was not as robust as initially desired. Both grab (waste rock) samples and tailings samples were taken from around discharge pipes 3 and 4. The assay results ranged from 200 to 204 ppm Ni for the grab samples and 40 to 46 ppm Ni for the tailings

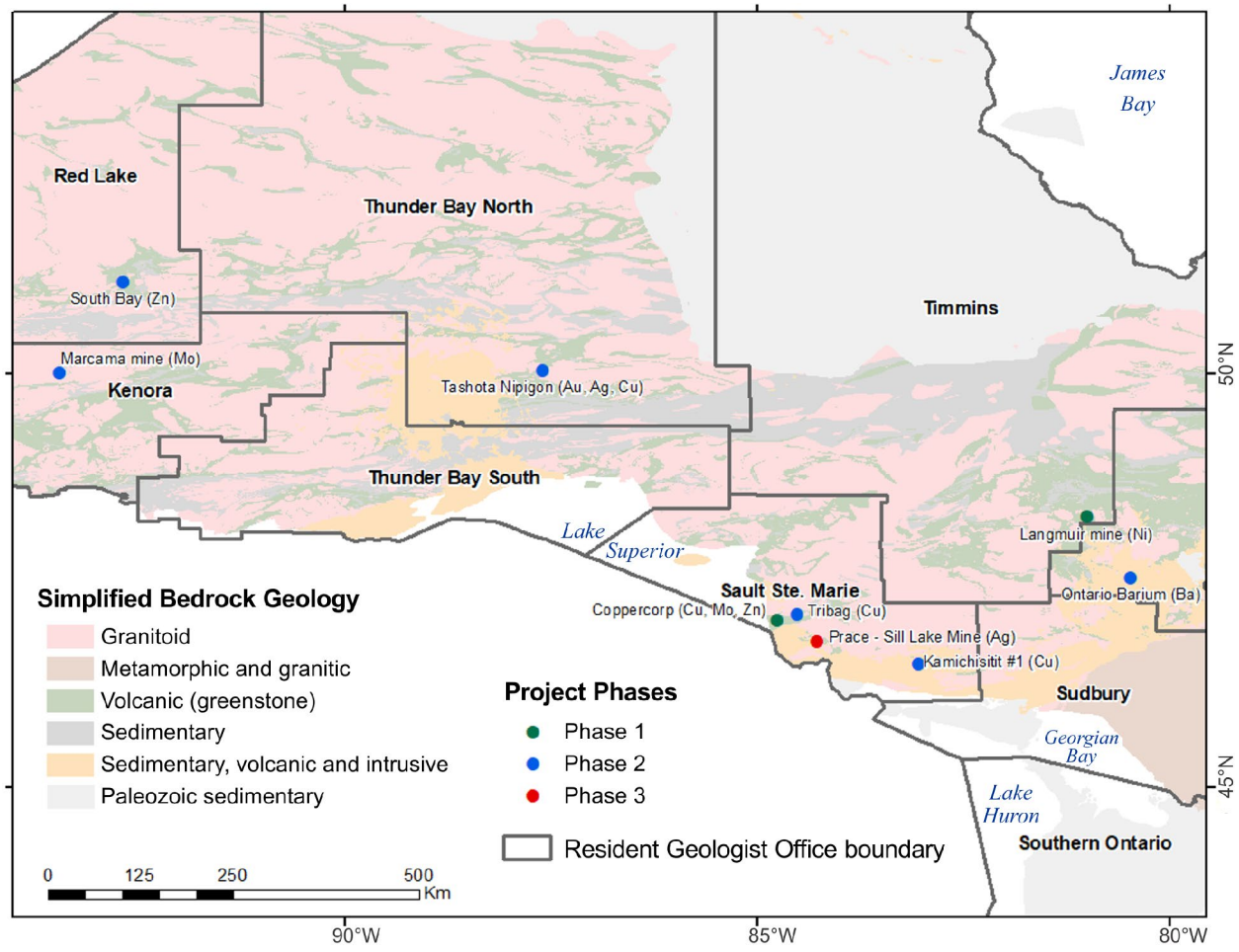


Figure 32.1. Sites for phase 1 (in green), phase 2 (in blue) and currently proposed phase 3 (in red) of the mine waste project, along with primary targeted commodities. Geology *from* Ontario Geological Survey (2011).

Table 32.1. Analytical values for phase 1 sampling (2021) at the Langmuir Mine, near Timmins, and the Coppercorp Mine near Sault Ste. Marie, Ontario. Average values are included for some samples.

Langmuir Mine waste samples AMIS number 10069 [a] OMI no. MDI42A06SE00006 [b]	**Sample Source**	**UTM Zone**	**Easting [c] (m)**	**Northing [c] (m)**	**Ni (ppm)**	**Co (ppm)**	**Cu (ppm)**	**Zn (ppm)**
Waste rock sample 1	Waste rock	17	499825	5354101	204	25	40	79
Waste rock sample 2	Waste rock	17	499801	5354109	200	25	41	67
Grab sample averages	Waste rock	17			202	25	40	71
Tailings sample 1	Near discharge pipes 3 and 4	17	499859	5354081	46	15	31	94
Tailings sample 2	Near discharge pipes 3 and 4	17	499873	5354071	44	15	31	72
Tailings sample 3	Near discharge pipes 3 and 4	17	499873	5354071	43	16	31	75
Tailings sample 4	Near discharge pipes 3 and 4	17	499859	5354094	44	15	30	72
Tailings sample 5	Near discharge pipes 3 and 4	17	499859	5354094	43	16	31	73
Tailings sample 6	Near discharge pipes 3 and 4	17	499762	5354120	42	15	30	70
Tailings sample 7	Near discharge pipes 3 and 4	17	499762	5354120	45	17	33	81
Tailings sample averages					44	15	310	76

Coppercorp Mine waste samples AMIS number 08061 OMI no. MDI41N02SW00004	**Sample Source**	**UTM Zone**	**Easting (m)**	**Northing (m)**	**Ni (ppm)**	**Co (ppm)**	**Cu (ppm)**	**Zn (ppm)**
Tailings sample 1	Tailings pond [d]	16	670872	5209848	41	31.3	1100	142
Tailings sample 2	Tailings pond [d]	16	670872	5209848	46	36.0	775	166
Tailings sample 3	Tailings pond [d]	16	670872	5209848	40	25.0	976	106
Tailings sample 4	Tailings pond [d]	16	670874	5209934	37	28.6	929	129
Tailings sample 5	Tailings pond [d]	16	670874	5209934	37	28.7	896	132
Tailings sample 6	Tailings pond [d]	16	670934	5210049	39	27.7	597	126
Tailings sample 7	Tailings pond [d]	16	670934	5210049	38	29.8	545	143
Tailings sample 8	Tailings pond [d]	16	670934	5210049	38	27.8	566	135
Tailings sample 9	Tailings pond [d]	16	671022	5209688	45	33.2	429	152
Tailings sample 10	Tailings pond [d]	16	670973	5209731	39	30.9	420	145
Tailings sample 11	Tailings pond [d]	16	670973	5209731	39	27.7	515	129
Tailings sample averages					40	30.0	668	139

[a] *Abandoned Mine Identifier (AMIS) data* from *Mines and Minerals Division (2022).*
[b] *Ontario Mineral Inventory (OMI) data* from *Ontario Geological Survey (2022) (note, the Ontario Mineral Inventory (OMI) database was previously known as the "Mineral Deposit Inventory" (MDI) database).*
[c] *All Universal Transverse Mercator (UTM) co-ordinates provided in North American Datum 1983 (NAD83).*
[d] *Collected from along the length of the tailings pond at random intervals, 11 samples in total.*

samples at soil depths ranging from 0.5 to 1 m. Table 32.1 summarizes the assay results from the 2021 sampling. All analyses were done by inductively coupled plasma mass spectrometry (ICP–MS). A second visit was planned for the 2022 field season to increase the diversity of samples from this site, including targeting discharge pipes 1 and 2.

The Coppercorp Mine was in operation from 1965 to 1972. Total mine production was over 10 000 t of copper (Tortosa 2002). The site is currently owned and maintained by the Crown. The Coppercorp Mine site was easily accessed and was thoroughly sampled across the tailings pond with no issues. The 11 tailings samples taken from across this site had copper concentrations between 418 and 1100 ppm Cu (*see* Table 32.1). Samples analyzed were collected from depths of 1 to 2 m and the highest copper contents were between 900 and 1100 ppm Cu (*see* Table 32.1).

Table 32.2. Site details for phase 2 of the tailings project.

Phase 2 Sites	Resident Geologist District	AMIS Number [a]	OMI Number [b]	UTM Zone	Easting [c] (m)	Northing [c] (m)	Commodity [d]
Marcama Mine	Kenora	06553	MDI52K03SW00011	15	468232	5540112	Mo
South Bay Mine	Red Lake	03892	MDI52N02SE00012	15	522471	5662301	Zn, Cu, Ag, In, Ge, Ga
Tribag Mine	Sault Ste. Marie	08068	MDI000000001285 MDI41N02SE000034	16	689136	5217719	Cu, Zn, W, Mo
Kamichisitit Mine	Sault Ste. Marie	00564	not applicable	17	343275	5151113	Cu
Tashota–Nipigon Mine	Thunder Bay North	02973	MDI42L04SE00005	16	458055	5543898	Cu, Ag, Bi
Langmuir Mine	Timmins	10069	MDI42A06SE00006	17	499859	5354094	Ni
Ontario Barium Mine	Kirkland Lake	08426	MDI41P15NE00003	17	517350	5304998	Ba

[a] *Abandoned Mine Identifier (AMIS) data* from *Mines and Minerals Division (2022).*
[b] *Ontario Mineral Inventory (OMI) data* from *Ontario Geological Survey (2022) (note, the Ontario Mineral Inventory (OMI) database was previously known as the "Mineral Deposit Inventory" (MDI) database).*
[c] *All UTM co-ordinates are provided in NAD83.*
[d] ***Abbreviations:*** *Ag, silver; Ba, barium; Bi, bismuth; Cu, copper; Ga, gallium; Ge, germanium; In, indium; Mo, molybdenum; Ni, nickel; Zn, zinc; W, tungsten.*

PHASE 2: PROVINCE-WIDE SAMPLING

Phase 2 of the project took place during the 2022 field season. Resident Geologist Program staff from across the province sampled 7 sites considered to have suitable tailings waste with the potential for critical minerals. The phase 2 sampled sites are described in the following paragraphs and are shown in Figure 32.1; more details for these sites are provided in Table 32.2. Results for phase 2 samples are pending, and details will be released at a future date.

Kenora District

The Kenora District has a historical occurrence of molybdenite hosted by granite, granite gneiss, quartz veins and pegmatite dikes in Redvers Township (Marcama Mine: Abandoned Mine Identifier 06553; MDI52K03SW00011). Previous exploration in the area included 2 diamond-drill holes and a grade of 1.41% MoS_2 from 180 pounds of removed material (Ontario Geological Survey 2022). The RGP staff attempted to sample this site, but were hampered by lack of access. The site may be moved to phase 3 of the project.

Red Lake District

The South Bay Mine is a historical volcanogenic massive sulphide deposit located in Dent Township, east of Red Lake, that was mined for zinc, copper and silver from 1971 to 1981 (MDI52N02SE00012). Production numbers during that time were 1 637 948 t at 11.06% Zn and 1.8% Cu (Lichtblau et al. 2015, p.24). The tailings have the potential for zinc, copper and silver. Indium, gallium and germanium may also be present, based on reported mineral occurrences in the vicinity (Lichtblau et al. 2015, p.24). A total of 5 separate areas at this site were sampled, with 16 samples collected in September 2022. Assay results are pending for this site.

Sault Ste. Marie District

Two prospective sites were identified, and sampling is planned in the fall of 2022 at the Tribag Mine and the Kamichisitit Mine. The Tribag Mine was a historical diatreme-hosted porphyry copper mine that operated in Nicolet Township in the 1960s and 1970s (Abandoned Mine Identifier 08068; MDI000000001285, MDI41N02SE00034). Production numbers for the Tribag Mine were 1 218 000 tons of copper, grading 1.52% Cu (*Northern Ontario Business*, June 10, 2022, www.northernontariobusiness.com/industry-news/mining/exploration-company-hopes-to-find-a-new-batchawana-copper-mine-next-to-an-old-one-5465007), with most of the ore coming from the Breton breccia. The mine closed in the 1970s because of falling copper prices; however, recent exploration has seen positive drill results (*Northern Ontario Business*, June 10, 2022, www.northernontariobusiness.com/industry-news/mining/exploration-company-hopes-to-find-a-new-batchawana-copper-mine-next-to-an-old-one-5465007). There is the potential for copper, zinc, tungsten and molybdenum in the tailings and waste rock at this site.

The Kamichisitit Mine (Abandoned Mine Identifier 00564) was also a historical copper mine that ceased production in the 1970s; the mine waste has the potential for additional copper recovery.

Thunder Bay North District

The Tashota–Nipigon site was an historical gold mine that ceased operation in the 1930s and received some further exploration in the 1960s (Abandoned Mine Identifier 02973; MDI42L04SE00005). The mine waste has the potential for copper, silver and bismuth. Access to the waste is difficult, and the first attempt to sample was unsuccessful. A new access route is being planned, and sampling is set to proceed in mid-October 2022.

Timmins District

The Timmins District has 1 site under consideration, the Langmuir Mine described in phase 1 above, with additional resampling planned for November 2022.

Kirkland Lake District

The Ontario Barium Mine, in Yarrow Township, is an historical barite mine that opened in 1917 and underwent testing and exploration throughout the 1940s (Abandoned Mine Identifier 08426; MDI41P15NE00003). The site has the potential for additional barite in the waste rock. The Ontario Barium site was sampled in August 2022. The sampling point was a test pit on the abandoned mine site. Assay results are pending.

PHASE 3: NEXT STEPS

Phase 3 of the project will involve analyzing the results from the phase 2 samples, resampling if necessary, and adding additional historically mined sites across both northern and southern Ontario for sampling. Phase 3 will involve all 9 RGP districts. More information about the next steps of the project will be released after the assay data from 2022 have been reviewed.

ACKNOWLEDGMENTS

Thank you to all staff members who contributed to this project, including Ethan Amyotte, Paul Malegus, Greg Paju, Barun Maity, Edwin Morelli, John Hechler, Marcus Burnham, Evan Hastie, Sonia Préfontaine and Michael Easton all of the OGS. Your work and assistance in project proposal writing and editing, sampling and analysis protocols, method development, and field work has been essential in moving this project forward. Special thanks also go to Monica Gaiswinkler Easton, and Paula Takats, for editorial assistance.

REFERENCES

Azadbakht, Z., Bennett, D., Maity, B.K., Bousquet, P., Daniels, C.M., Hinz, S.L.K., Morelli, E. and Dorland, G. 2022. Report of Activities 2021, Resident Geologist Program, Timmins Regional Resident Geologist Report: Timmins and Sault Ste. Marie Districts; Ontario Geological Survey, Open File Report 6384, 151p.

International Energy Agency 2022. The role of critical minerals in clean energy transitions, revised March 2022; International Energy Agency, Paris, World Energy Outlook Special Report, 283p., www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions [accessed November 18, 2022].

Lichtblau, A.F., Ravnaas, C., Storey, C.C., Tims, A., Debicki, R.L., Pettigrew, T.K., Wilson, A.C. and Wetendorf, J. 2015. Report of Activities 2014, Resident Geologist Program, Red Lake Regional Resident Geologist Report: Red Lake and Kenora Districts; Ontario Geological Survey, Open File Report 6301, 83p.

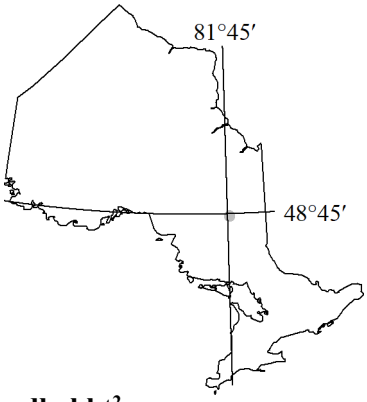
Mines and Minerals Division 2022. Abandoned Mines Information System Inventory; Ontario Ministry of Mines, Mines and Minerals Division, Abandoned Mines Information System Inventory (April 2022 update), online database.

Ontario Geological Survey 2011. 1:250 000 scale bedrock geology of Ontario; Ontario Geological Survey, Miscellaneous Release—Data 126 – Revision 1.

——— 2022. Ontario Mineral Inventory; Ontario Geological Survey, Ontario Mineral Inventory (October 2022 update), online database.

Tortosa, D. 2002. Geological report on the Coppercorp property of Amerigo Resources Ltd., Mamainse Point area, Ontario, prepared for Amerigo Resources Ltd.; technical report, Amerigo Resources Ltd., filed October 10, 2002 with SEDAR®, *see* SEDAR Home Page, 61p.

33. Geology, Geochemistry and Mineralogy of the Enid Creek Cobalt-Copper-Nickel-Palladium-Platinum Prospect, Loveland Township, Northwest of Timmins, Ontario



E.H. van Hees[1,2], S.A. Clarke[3], D.C. Crabtree[3], A.S. Péloquin[4] and Z. Azadbakht[2]

[1]Department of Chemistry, Oakland University, Rochester, Michigan, USA 48309
[2]Resident Geologist Program, Ontario Geological Survey, Timmins, Ontario P0N 1H0
[3]Geoscience Laboratories, Ontario Geological Survey, Sudbury, Ontario P3E 6B5
[4]Resident Geologist Program, Ontario Geological Survey, Sudbury, Ontario P3E 6B5

INTRODUCTION

A massive sulphide sample, collected at 320 feet (97.5 m) in Hollinger Consolidated Gold Mines Ltd. exploration drill-hole EC-16, was 1 of 10 samples selected by the staff of the Timmins Resident Geologist's office for chemical analysis because there were no geochemical data publicly available.

Hollinger Consolidated Gold Mines Ltd. drilled exploration drill-hole EC-16 in Loveland Township in 1968 (collared at Universal Transverse Mercator (UTM) 454130E 5389330N, North American Datum 1983 (NAD83), Zone 17) (MacKenzie 1968). The core was donated to the Resident Geologist Program and has been stored in the Timmins Drill Core Library.

Analysis of this sample indicated it contained 1.77 ppm Bi, 1480 ppm Co, 1926 ppm Cu, 21 290 ppm Ni, 2.06 ppm Pd, 0.32 ppm Pt, 33.4 ppm Se and 7.33 ppm Te (van Hees 2019). That resulted in additional analysis, by the Ontario Geological Survey Geoscience Laboratories, of nearby samples collected from telescoped drill core (2 inches every 5 feet (5 cm every 1.52 m)) containing disseminated sulphides from 200 to 350 feet (~61 to 106.7 m). Those analyses produced anomalous arsenic, bismuth, cobalt, copper, nickel, palladium, platinum, selenium and tellurium values over 95 feet (29 m) of core (van Hees 2019) and warranted research to identify what minerals host these elements.

GEOCHEMICAL AND MINERALOGICAL ANALYSIS

This study was conducted to establish 1) if cobaltite or pentlandite is present; 2) what mineral(s) host cobalt and nickel if there is no cobaltite or pentlandite present; 3) what minerals contain palladium and platinum; 4) what minerals host the palladium and platinum minerals; and 5) what copper phases are present.

The wall-rock geochemistry was characterized using X-ray fluorescence (XRF) and loss-on-ignition analysis (Geoscience Laboratories test methods XRF-M01, XRF-T05 and LOI-4ST) on 30 core samples between 200 and 350 feet (61 m and 106.7 m; sample 320 feet (97.5 m) was analyzed using test method IAT-100 because of the high sulphide content). These samples were also analyzed using X-ray diffraction to determine the wall-rock mineralogy. Core samples were relogged and polished thin sections examined to determine grain size of the wall rocks.

Summary of Field Work and Other Activities, 2022,
Ontario Geological Survey, Open File Report 6390, p.33-1 to 33-7.

© King's Printer for Ontario, 2022

Optical and electron microscopy studies of 8 polished thin sections cut from samples at 245 feet (74.6 m), 255 feet (77.7 m), 285 feet (86.9 m), 315 feet (96.0 m), 320 feet (97.5 m), 321 feet (97.8 m) and 325 feet (99.1 m) were completed to identify the minerals that contain the arsenic, bismuth, cobalt, copper, nickel, palladium, platinum, selenium and tellurium values reported by van Hees (2019).

WHOLE-ROCK GEOCHEMICAL RESULTS AND INTERPRETATION

Major element composition of the 30 wall-rock samples indicate that they are calc-alkaline and plot between andesite and komatiitic basalt on the Jensen cation diagram (Figure 33.1):

- 200 to 255 feet (61–77.7 m):
  examination of archived drill-hole EC-16 core samples indicates they are a coarse-grained diorite (possibly porphyritic basalt) or coarse-grained gabbro as logged by MacKenzie (1968).
  - ♦ 200 to 230 feet (61–70.1 m): samples plot in the calc-alkaline, high-magnesium and komatiitic basalt fields (Figures 33.1 and 33.2).
  - ♦ 235 to 255 feet (71.6–77.7 m): samples plot in the andesite and basalt fields (*see* Figures 33.1 and 33.2).
  - ♦ Their trace element compositions straddle the basalt and andesite field boundaries (*see* Figure 33.2).

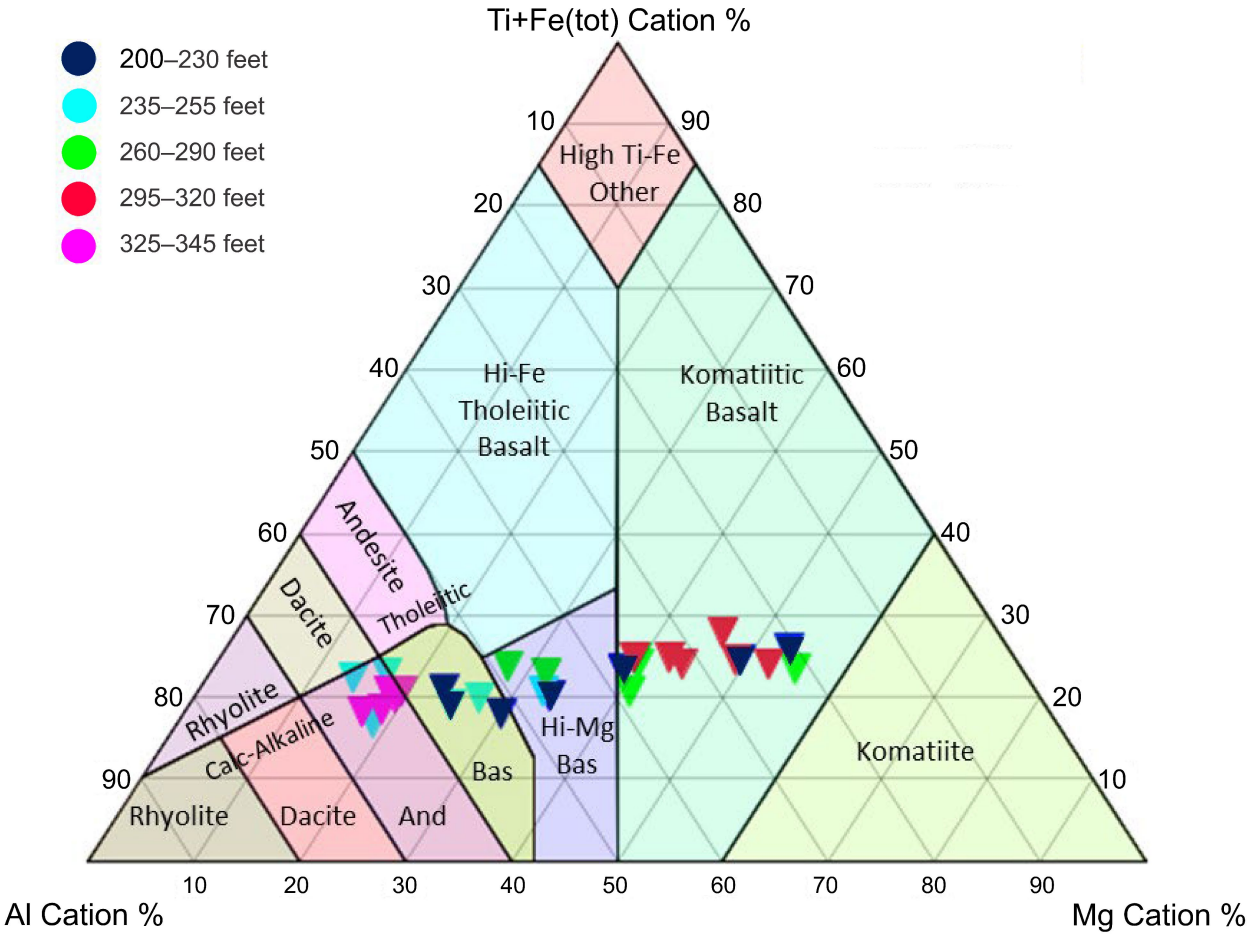


Figure 33.1. Jensen cation plot (Jensen 1976) for archived Hollinger Consolidated drill-hole EC-16 core samples that were collected at intervals of 5 feet (1.52 m) starting at 200 to 345 feet (61 to 105.2 m). Abbreviations: And = andesite; Bas = basalt.

- 260 to 320 feet (79.2–97.5 m) (above massive sulphide unit):
  examination of archived drill-hole EC-16 core samples identified that they are coarse-grained gabbro as logged by MacKenzie (1968).
  - ♦ 260 to 290 feet (79.2–88.4 m): gabbro samples plot mostly as high-magnesium basalt (*see* Figures 33.1 and 33.2).
  - ♦ 295 to 320 feet (89.9–97.5 m): gabbro samples plot as komatiitic basalt (*see* Figures 33.1 and 33.2).
- 325 to 345 feet (99.1–105.1 m) (below massive sulphide unit):
  examination of archived drill-hole EC-16 core samples found aphanitic rock with major and trace element compositions that plot as andesites (*see* Figures 33.1 and 33.2).

The lithogeochemical and textural results indicate that drill-hole EC-16 encountered 3 different rock units between 200 and 345 feet (61 and 105.2 m). These units are

- diorite between 200 and 255 feet (61 to 77.7 m)
- gabbro between 260 and 320 feet (79.2 to 97.5 m)
- andesite between 325 and 345 feet (99.1 to 105.2 m).

The telescoped core (2 inches collected every 5 feet (5 cm every 1.52 m)) available for this study precludes commenting on how the rock units relate to each other, except to say that the massive sulphide unit lies on the gabbro–andesite boundary as logged for drill-hole EC-16 by MacKenzie (1968).

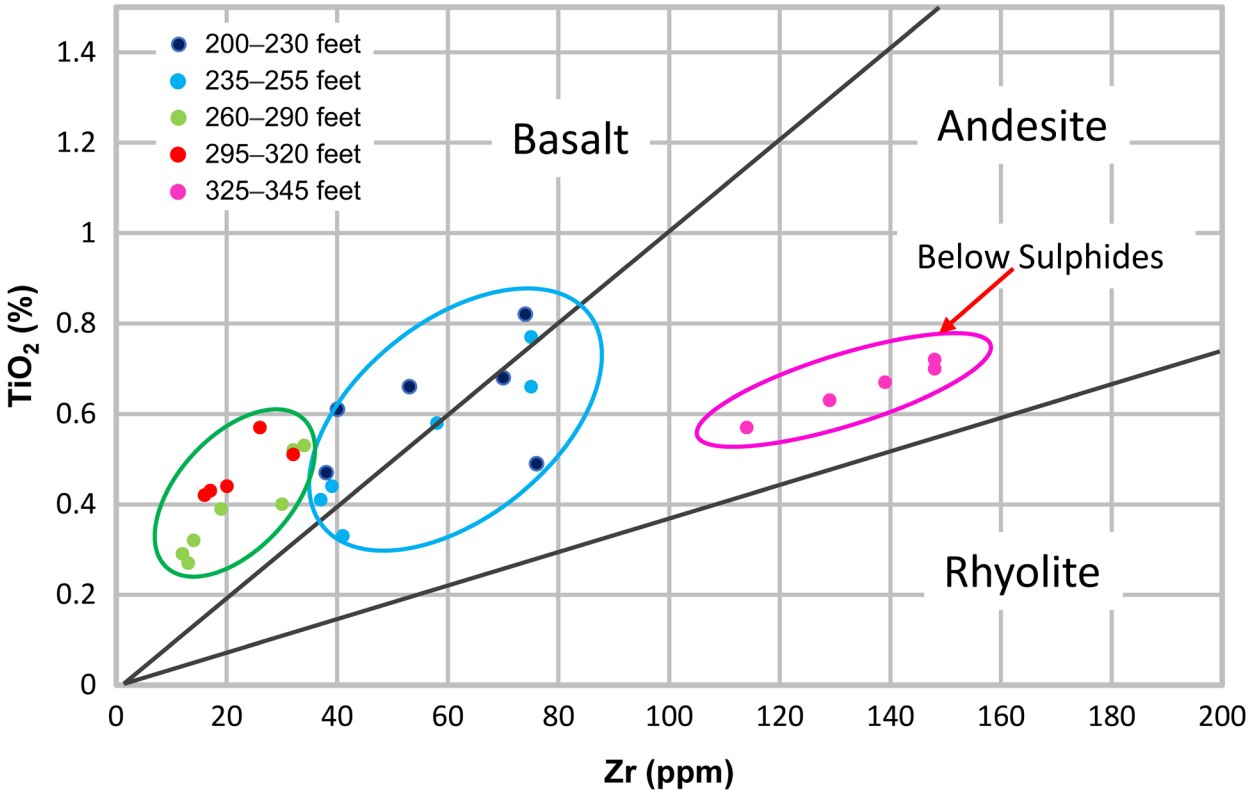


Figure 33.2. Zirconium (Zr) versus TiO_2 plot (MacLean 1990) for Hollinger Consolidated drill-hole EC-16 core samples that were collected between 200 feet (61 m) and 345 feet (105.2 m). Samples at various depths in the hole separated into 5 different groups (colours correspond to Figure 33.1). Pink dots are samples from beneath the massive sulphides, and were collected at 325 feet (99.1 m), 330 feet (100.6 m), 335 feet (102.1 m), 340 feet (103.6 m) and 345 feet (105.2 m).

MINERALOGY OF THE HOST ROCKS

Wall-rock samples from 245 feet (76.7 m), 255 feet (77.7 m), 285 feet (86.8 m), 315 feet (96.0 m), 320 feet (97.5 m), 321 feet (97.8 m) and 325 feet (99.1 m) in drill-hole EC-16 were examined using X-ray diffraction on pulp samples and optical microscopy on 8 polished thin sections. These studies found that all 7 samples consisted primarily of albite, amphibole, chlorite, epidote, mica (sericite) and carbonate. This mineral assemblage is interpreted to indicate that most primary minerals have been altered by hydrothermal fluids. Primary albite, present in all samples, appears to have been saussuritized by hydrothermal fluids. Quartz observed in narrow veinlets in the sample at 325 feet (99.1 m), and found in 6 of 8 polished thin sections, is consistent with a hydrothermal origin.

PLATINUM GROUP MINERAL ANALYSIS

Geoscience Laboratories produced high-resolution montaged backscattered electron images of 8 polished thin sections using AZtec® software on the JEOL IT-500HR FEG scanning electron microscope equipped with an Oxford Instruments® 80 mm^2 energy dispersive SDD X-ray spectrometer. Each thin section was examined using Feature® analysis to explore for a suite of minerals including platinum group minerals. Feature® analysis allows the analyst to explore for minerals by manipulating

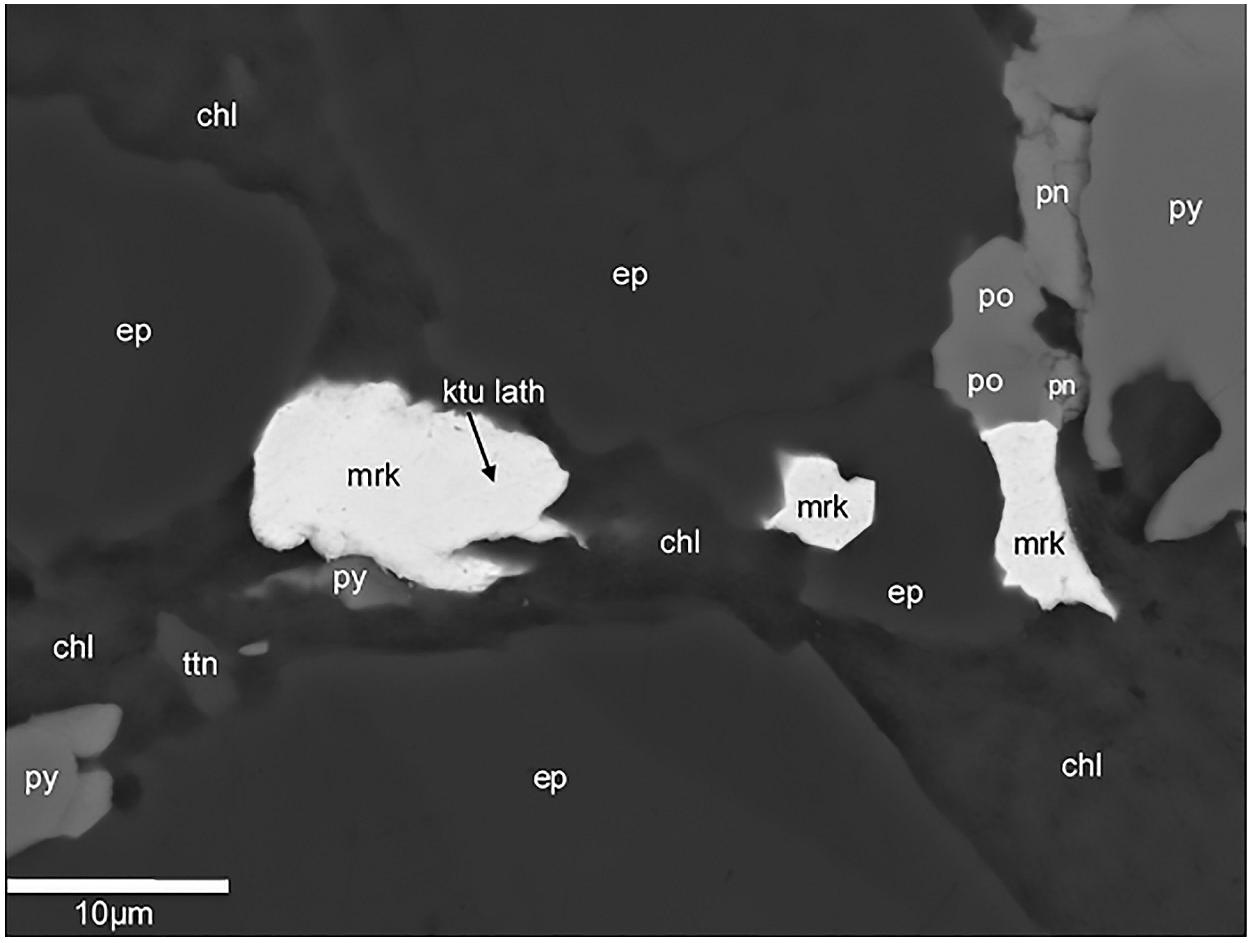


Photo 33.1. Backscattered electron image of polished thin section EC16-321S. Kotulskite (ktu) and merenskyite (mrk) are hosted in silicate minerals and attached to pentlandite (pn) and pyrrhotite (po). Other abbreviations: chl = chlorite; ep = epidote; ttn = titanite; py = pyrite.

Table 33.1. Summary of results for sulphide and platinum group minerals following analysis by scanning electron microscope.

Feet (m)	Is cobaltite[1] (CoAsS) (cob) or pentlandite (pn) present?			If no cob or pn, where is Co or Ni found?	Where are Pd and Pt found?		What copper phases are present?
	Cobaltite	Details	Pentlandite		Palladium (Pd)	Platinum (Pt)	
245 (76.7)	cob absent		pn present		mrk	spy	cp
255 (77.7)	cob present	7 grains	pn present		mrk	No Pt-bearing minerals	cp
285 (86.8)	cob absent		pn present	some Co in pn	mrk/ktu	No Pt-bearing minerals	cp
315 (96.0)	cob present	1 Rh-bearing FeAsCoNi sulphide	pn present		mrk/ktu	spy	cp
320 (97.5) [2]	cob present	8 very small grains intergrown with mrk	pn present		mrk	spy	cp
321 (97.8)	cob absent		pn present	some Co in pn	mrk	spy	cp
325 (99.1)	cob present	26 grains found during Feature® analysis	pn absent		bdl in geochem	bdl in geochem	cp

[1] *Software was set to find platinum group minerals (PGMs), so there might be more cobaltite (CoAsS) present.*
[2] *Results for 2 polished thin sections (320 and 320s) were combined in this table.*
Mineral abbreviations: *cob = cobaltite; cp = chalcopyrite; ktu = kotulskite; mrk = merenskyite; pn = pentlandite; spy = sperrylite.*
Other abbreviation: *bdl = below detection limit; geochem = geochemical data.*

Table 33.2. Platinum and palladium mineral grain abundances determined by scanning electron microscopy analyses.

Feet (m)	Total PGM Grains	Palladium- (Pd-) rich tellurium (Te) (±Sb, Bi, Ni, Fe)								Sperrylite ($PtAs_2$)			
		Kotulskite (Pd,Ni,Fe)(Te,Bi,Sb)				Merenskyite (Pd,Fe,Ni)(Te,Sb,Bi)$_2$							
		Grains	Min size [1] µm	Max size [1] µm	Avg size [1] µm	Grains	Min size [1] µm	Max size [1] µm	Avg size [1] µm	Grains	Min size [1] µm	Max size [1] µm	Avg size [1] µm
245 (76.7)	20	0				18	1.65	29.31	4.44	2	1.88	5.21	3.54
255 (77.7)	3	0				3	1.68	14.53	7.07	0			
285 (86.8)	3	2	3.46	5.24	4.35	1	2.66			0			
315 (96.0)	30	2	4.24	4.86	4.55	22	1.68	10.43	3.45	6	1.33	2.06	1.75
320 (97.5) [2]	120	12	0.81	7.73	2.89	105	0.57	11.73	2.65	3	0.57	1.99	1.12
321 (97.8)	71	0				52	1.68	16.39	4.85	19	1.68	7.37	2.85
325 (99.1)	0	0				0				0			

[1] *Size is reported as a calculated circular diameter.*
[2] *Results for 2 polished thin sections (320 and 320s) were combined in this table.*
Abbreviations: *Min = minimum; Max = maximum; Avg = average; µm = microns; PGM = platinum group minerals.*

backscattered electron imaging thresholds. The imaging conditions were 60× magnification, 4096 resolution, 5 µs dwell time for image acquisition, 2 second scan of whole features (energy-dispersive X-ray spectroscopy analysis), and accelerating voltage of 20 kV and 1.25 nA beam current. The smallest mineral grain that could be resolved was ~0.60 µm in diameter. Backscattered electron Feature® analysis identified cobaltite, chalcopyrite, native gold, kotulskite ($Pd(Te,Bi)_{2-x}$), merenskyite ($PdTe_2$), pyrite, pyrrhotite, pentlandite and sperrylite (Tables 33.1 and 33.2). The greatest concentration of kotulskite, merenskyite and sperrylite grains occur in the gabbro at 315 feet (96.0 m), 320 feet (97.5 m) and 321 feet (97.8 m), just above the andesite–gabbro contact (*see* Table 33.2). The second highest concentration of merenskyite and sperrylite grains is found in the sample at 245 feet (74.7 m), which appears to be a diorite, close to the gabbro contact. Eight gold grains occur with platinum group minerals at 321 to 315 feet (97.8 to 96.0 m) and 3 gold grains at 245 feet (74.7 m). Pentlandite and pyrrhotite occur in 6 of 8 polished thin sections (*see* Table 33.1). Kotulskite, merenskyite and sperrylite are associated with these sulphides and the wall-rock silicate minerals (Photo 33.1). Cobalt, in the 0.1 to 3 weight % range, was detected in all pentlandite. Chalcopyrite occurs in all polished thin sections (*see* Table 33.1). These sulphide, telluride and arsenide minerals were likely introduced by the hydrothermal fluids that formed the suite of silicate alteration minerals (*see* Photo 33.1).

COMPARABLE DEPOSITS

The telluride, sulphide and arsenide mineral assemblage, plus average Pd/Pt ratios of 11.06 (range = 3.3 to 16.9: van Hees 2019), are comparable to those found in the Lac des Iles deposit (Watkinson and Dunning 1979; Cabri and Laflamme 1979; Barnes and Gomwe 2011). Other mineral deposits with similar mineral suites include the Marathon deposit (Good, Cabri and Ames 2017), and Boston Creek (Stone et al. 1992) and Shebandowan Mines (Watkinson et al. 1978).

ACKNOWLEDGMENTS

Aaron Bustard, the Timmins District Geologist (Acting) in early 2018, selected the massive sulphide sample from Hollinger Consolidated drill-hole EC-16 that initiated this and previous studies on the Enid Creek cobalt-copper-nickel-palladium-platinum prospect. Dawn-Ann Metsaranta facilitated obtaining additional analyses required to complete this study. This manuscript has benefitted from reviews by Sonia Préfontaine and Michael Easton (OGS Earth Resources and Geoscience Mapping Section), and editing by Monica Gaiswinkler Easton (OGS Publication Services).

POST-PUBLICATION ADDENDUM AND ERRATA

In January 2023, following publication (in December 2022) of these related analytical data, the Timmins Resident Geologist Office staff were contacted about the content of this article. After a search of the Timmins Drill Core Library, staff found there existed 2 separate boxes of donated company drill core, both labelled as "box 155406". One box contained core from drill-hole L-13 and the other box contained core from drill-hole EC-16. Further investigation revealed that the drill core studied in this project was, in fact, from drill-hole EC-16, rather than from drill-hole L-13. The analytical data reported have not been affected; however, the location of the drill hole was corrected and the descriptions of the examinations of the drill core required modifications. This version, as of February 2023, corrects the errors.

REFERENCES

Barnes, S-J. and Gomwe, T.S. 2011. The Pd deposits of the Lac des Iles Complex, northwestern Ontario; *in* Magmatic Ni-Cu and PGE deposits: Geology, geochemistry, and genesis, Reviews in Economic Geology, v.17, p.351-370.

Cabri, L.J. and Laflamme, J.H.G. 1979. Mineralogy of samples from Lac des Iles area, Ontario; Energy, Mines and Resources, Canada, Canada Centre for Mineral and Energy Technology, CANMET Report 79-27, 20p.

Good, D.J., Cabri, L.J. and Ames, D.E. 2017. PGM Facies variations for Cu-PGE deposits in the Coldwell alkaline complex, Ontario, Canada; Ore Geology Reviews, v.90, p.748-771.

Jensen, L.S. 1976. A new cation plot for classifying subalkalic volcanic rocks; Ontario Division of Mines, Miscellaneous Paper 66, 22p.

MacKenzie, C.D. 1968. Drill log for diamond-drill hole EC-16 (completed November 15, 1968), Loveland Township, for Hollinger Consolidated Gold Mines Ltd.; Timmins Resident Geologist's office, NTS 42 A/12NE, file T-794, 3p.

MacLean, W.H. 1990. Mass change calculations in altered rock series; Mineralium Deposita, v.25, p.44-49.

Ontario Geological Survey 2022. Ontario Mineral Inventory; Ontario Geological Survey, Ontario Mineral Inventory (September 2022 update), online database.

Stone, W.E., Fleet, M.E., Crocket, J.H. and Kingston, D.M. 1992. Platinum-group minerals in pyroxenite from the Boston Creek flow basaltic komatiite, Abitibi greenstone belt, Ontario; The Canadian Mineralogist, v.30, p.109-119.

Vanderklift, W., Van Luven, C. and Voormeij, D. 2005. Report on Enid Creek property, Loveland Township, Ontario, prepared for Inco Technical Services Limited Exploration; International Explorers and Prospectors Inc., internal company report, 18p.

van Hees, E.H. 2019. Exploration for disseminated nickel-copper mineralization; *in* Ontario Geological Survey, Resident Geologist Program, Recommendation for Exploration 2018–2019, p.76-80.

Watkinson, D.H. and Dunning, G. 1979. Geology and platinum-group mineralization, Lac-des-Iles Complex, northwestern Ontario; The Canadian Mineralogist, v.17, p.453-462.

Watkinson, D.H., Hak, J., Morton, P. and Johan, Z. 1978. Merenskyite from the Shebandowan nickel-copper mine, northwestern Ontario; The Canadian Mineralogist, v.16, p.659-663.

Index of Authors (with corresponding article numbers)

A

Amyotte, E.G., 31
Atasiei, D., 20
Azadbakht, Z., 33

B

Béland Otis, C., 23
Beneteau, S.B., 1
Bennett, D.J. , 3, 32
Biswas, S., 16
Bocking, C.N., 25
Brunton, F.R., 19, 20, 21
Burnham, O.M., 26, 27
Burt, A.K., 24
Buyers, A., 6

C

Clarke, S.A., 33
Cormier, R., 4
Crabtree, D.C., 33
Cundari, R.M., 30

D

Di Iorio, T., 25
Duguet, M., 4, 14

E

Easton, R.M., 4, 12
Evangelatos, J., 16

F

Foubister, S., 25

G

Gemmell, T.P., 6
Gibson, H.L., 15
Gordon, C.A., 13

H

Hagedorn, G.W., 24
Hahn, K.E., 22
Hargreaves, J.C., 28
Hastie, E.C.G., 14, 15
Hechler, J.H., 4

J

Jin, J., 19, 20
Jonsson, J.R.B., 31

K

Kalmo, K.J.J., 2
Kamo, S.L., 5
Keating, G.L., 29
Kurcinka, C.E., 11, 31
Kurucz, S.V., 31

L

Levesque, M.D., 3

M

MacDonald, P.J., 5, 14
Marich, A.S., 17
Meade, S.R., 10
Melo-Gómez, J.D., 15
Metsaranta, R.T., 9, 11
Mulligan, R.P.M., 18

P

Paju, G.F., 31
Paterson, R.H., 19
Péloquin, A.S., 33
Perrouty, S., 8
Petrus, J.A., 15
Phillips, A.R., 19, 21
Préfontaine, S., 4

R

Robichaud, L., 4, 8

T

Tait, K.T., 15
Tsujita, C.J., 20

V

van Hees, E.H., 33
Vice, L.E.D., 7, 8

Y

Yeung, K.H., 19, 20, 21

Metric Conversion Table

Conversion from SI to Imperial			Conversion from Imperial to SI		
SI Unit	*Multiplied by*	*Gives*	*Imperial Unit*	*Multiplied by*	*Gives*
		LENGTH			
1 mm	0.039 37	inches	1 inch	**25.4**	mm
1 cm	0.393 70	inches	1 inch	**2.54**	cm
1 m	3.280 84	feet	1 foot	**0.304 8**	m
1 m	0.049 709	chains	1 chain	20.116 8	m
1 km	0.621 371	miles (statute)	1 mile (statute)	**1.609 344**	km
		AREA			
1 cm^2	0.155 0	square inches	1 square inch	**6.451 6**	cm^2
1 m^2	10.763 9	square feet	1 square foot	**0.092 903 04**	m^2
1 km^2	0.386 10	square miles	1 square mile	2.589 988	km^2
1 ha	2.471 054	acres	1 acre	0.404 685 6	ha
		VOLUME			
1 cm^3	0.061 023	cubic inches	1 cubic inch	**16.387 064**	cm^3
1 m^3	35.314 7	cubic feet	1 cubic foot	0.028 316 85	m^3
1 m^3	1.307 951	cubic yards	1 cubic yard	0.764 554 86	m^3
		CAPACITY			
1 L	1.759 755	pints	1 pint	0.568 261	L
1 L	0.879 877	quarts	1 quart	1.136 522	L
1 L	0.219 969	gallons	1 gallon	**4.546 090**	L
		MASS			
1 g	0.035 273 962	ounces (avdp)	1 ounce (avdp)	28.349 523	g
1 g	0.032 150 747	ounces (troy)	1 ounce (troy)	**31.103 476 8**	g
1 kg	2.204 622 6	pounds (avdp)	1 pound (avdp)	**0.453 592 37**	kg
1 kg	0.001 102 3	tons (short)	1 ton(short)	**907.184 74**	kg
1 t	1.102 311 3	tons (short)	1 ton (short)	**0.907 184 74**	t
1 kg	0.000 984 21	tons (long)	1 ton (long)	**1016.046 908 8**	kg
1 t	0.984 206 5	tons (long)	1 ton (long)	**1.016 046 9**	t
		CONCENTRATION			
1 g/t	0.029 166 6	ounce (troy) / ton (short)	1 ounce (troy) / ton (short)	34.285 714 2	g/t
1 g/t	0.583 333 33	pennyweights / ton (short)	1 pennyweight / ton (short)	1.714 285 7	g/t

OTHER USEFUL CONVERSION FACTORS

	Multiplied by	
1 ounce (troy) per ton (short)	31.103 477	grams per ton (short)
1 gram per ton (short)	0.032 151	ounces (troy) per ton (short)
1 ounce (troy) per ton (short)	20.0	pennyweights per ton (short)
1 pennyweight per ton (short)	0.05	ounces (troy) per ton (short)

*Note: Conversion factors in **bold** type are exact. The conversion factors have been taken from or have been derived from factors given in the* Metric Practice Guide for the Canadian Mining and Metallurgical Industries*, published by the Mining Association of Canada in co-operation with the Coal Association of Canada.*

ISSN 0826-9580 (print)
ISBN 978-1-4868-6588-8 (print)

ISSN 1916-6117 (online) ISBN
978-1-4868-6589-5 (PDF)