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Buse, S., Lewis, D. and Magnus, S. 2009. Field investigations in the Lumby Lake greenstone belt, northwestern Ontario: new insights into the geology, structure and economic potential; *in* Summary of Field Work and Other Activities 2009, Ontario Geological Survey, Open File Report 6240, p.15-1 to 15-15.

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**Ontario Geological Survey  
Open File Report 6240**

**Summary of Field Work  
and Other Activities  
2009**

**2009**





ONTARIO GEOLOGICAL SURVEY

Open File Report 6240

Summary of Field Work and Other Activities 2009

Edited by

C.L. Baker, R.I. Kelly, J.A. Ayer, R.M. Easton, G.M. Stott, J.R. Parker and T. Brown

2009

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:

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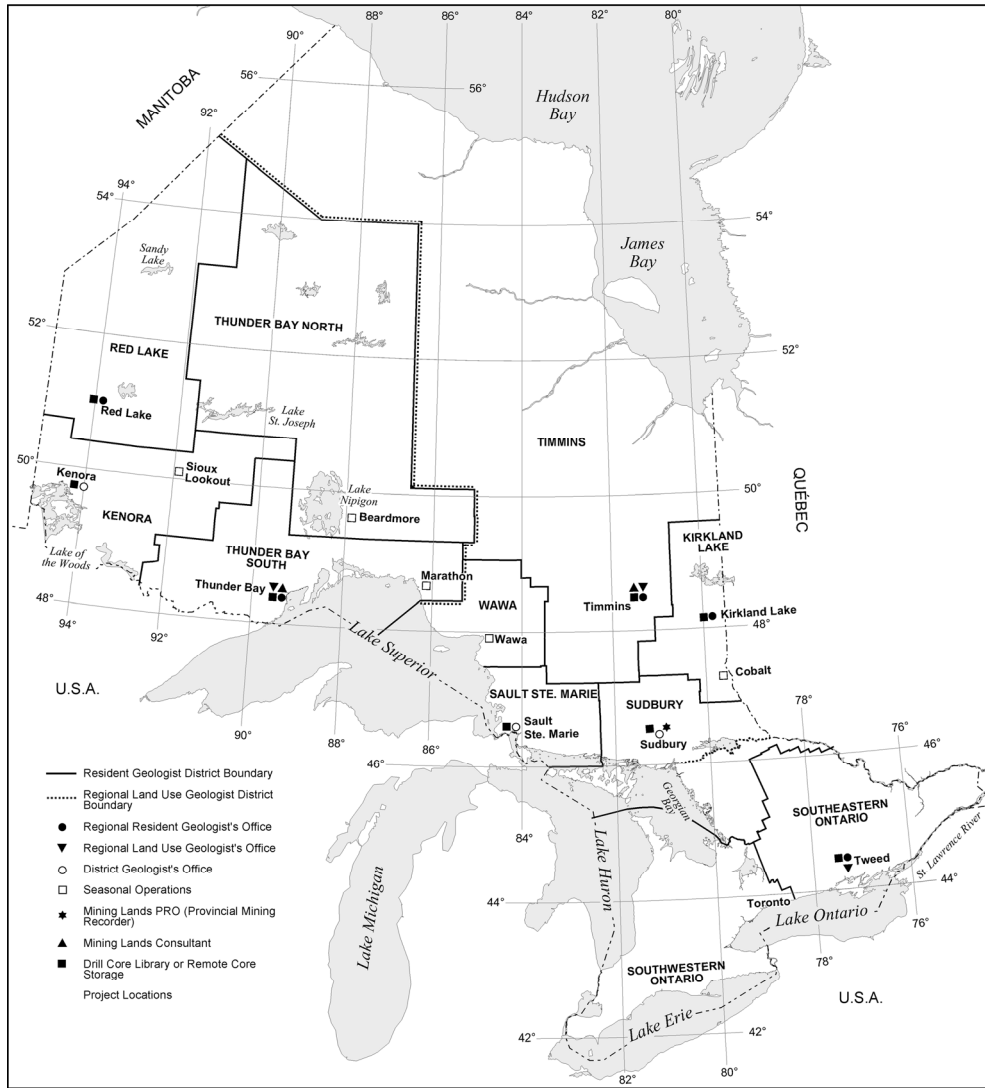
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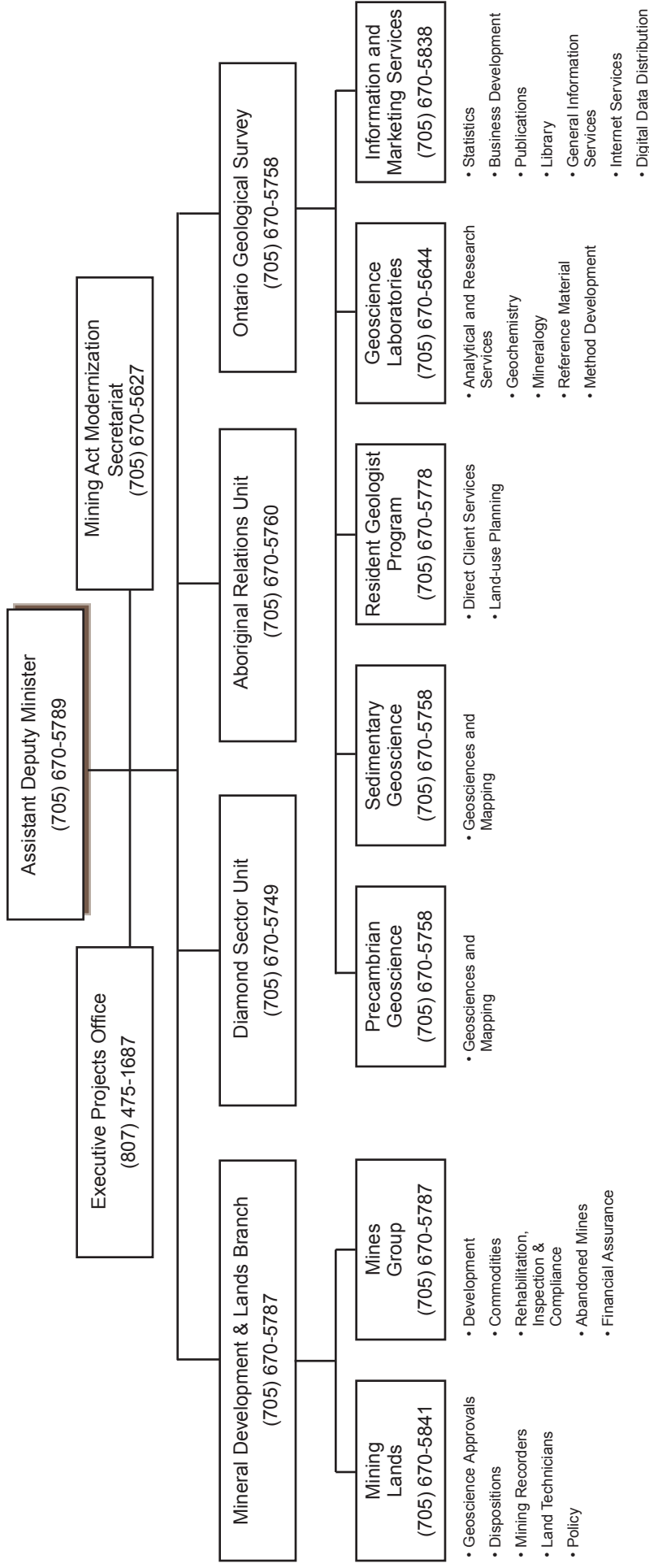


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Ministry of Northern Development, Mines and Forestry  
Mines and Minerals Division



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# 1. The Ontario Geological Survey Branch

J.A. Fyon<sup>1</sup>

<sup>1</sup>Director, Ontario Geological Survey

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## INTRODUCTION

The Ontario Geological Survey's (OGS) mission is to provide the citizens and institutions of Ontario with earth science data, information, and knowledge that are relevant, accessible and credible: relevant to Ontario's quality of life achieved through economic prosperity, environmental quality, and public safety and the range of public policy issues that will benefit from considering geoscience information; accessible to the global citizen who needs to access the geoscience data; and credible to assure the user that the OGS geoscience data and advice are independent, accurate, and objective.

The OGS undertakes a systematic and comprehensive inventory of the geological framework and processes that continue to shape Ontario. This understanding includes Ontario's rocks, deposits left by the glaciers, and the Earth resources contained within the rocks and glacial deposits. The Earth resources include the mineral resources within the rocks and glacial deposits; groundwater aquifers; and renewable (e.g., ground heat) and non-renewable (e.g., hydrocarbon) energy endowment and potential. The OGS geoscience data, information and knowledge describing the land are fundamental to support the Crown's mineral resource stewardship responsibility; to help inform decision-makers in the formulation of policies required to ensure the safe, sustainable management of Ontario's environment, adaptation to climate change, and development of mineral, energy and groundwater resources; and to help inform decision-makers considering economic development related to Earth resources. These OGS geoscience goods and services support land-use planning decisions, Earth resource investment decisions, and help identify sustainable, socio-economic development options for aboriginal and non-aboriginal communities. The OGS is the steward of a large amount of public geoscience data and provides public access to these knowledge resources.

The OGS undertakes several functions: a) mapping of bedrock and surficial geological materials; b) making an inventory of and assessing Ontario's potential for mineral, groundwater, and some types of energy resources; c) providing objective geoscience information for consideration during land-use planning; d) identifying geological characteristics relevant to public health and safety; e) publishing and marketing information on Ontario's landmass and its mineral, groundwater aquifer, and some types of energy resource endowments.

The OGS engages with Aboriginal communities and provides enhanced information to Aboriginal communities regarding the local geology and mineral sector activity taking place in proximity to a community. This engagement and communication is a pre-requisite and foundation to successful field project implementation and helps inform community and related Government decisions.

The OGS comprises the following administrative units: Precambrian Geoscience Section; Sedimentary Geoscience Section; Resident Geologist Program; Geoscience Laboratories; and Information and Marketing Services.

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*Summary of Field Work and Other Activities 2009,  
Ontario Geological Survey, Open File Report 6240, p.1-1 to 1-5.*

## **ENHANCED GEOSCIENCE PROGRAM**

In 2008, Ministry Executive endorsed an enhanced OGS geoscience mandate. As part of the Ontario Government's spring 2008 budget, the Province allocated \$5 million to MNDMF to support this enhanced geoscience mandate, which included 10 new positions. The Government's expectations included identification of new economic opportunities attributed to Ontario's geological and mineral resources, energy, and groundwater endowment and new or existing geoscience to be available to inform a broader set of public policy priorities. This enhanced mandate includes the traditional bedrock mapping in geographic areas in support of mineral development and the application of geoscience goods and services to help inform and address issues related to the environment (e.g., groundwater, Climate Change) and public health and safety. The enhanced geoscience mandate affords a unique opportunity for the OGS to apply its geoscience goods and services to help address issues faced by a broader clientele within and outside of Government.

Administrative adjustments taken include increased budgets for the Geoscience Laboratories and the Resident Geologist Program; increased geoscience staff for the Resident Geologist Program and the Sedimentary Geoscience Section; increased technical support for the Precambrian Geoscience Section and the Information and Marketing Services unit. In addition to our geological mapping function, the ISO 17025:2005 certified OGS Geoscience Laboratories continues to follow its capital reinvest strategy to ensure it has the technical ability to continue to meet the needs of the rest of the OGS and the external clients, including the Department of Earth Sciences, Laurentian University, the Centre for Excellence in Mining Innovation, and other broad public sector organizations across North America.

## **FACTORS INFLUENCING THE GEOSCIENCE PROGRAM**

During the 2009–2010 program planning, the following Government priorities influence the OGS geoscience program.

### **Far North Land-Use Planning Initiative**

On July 14, 2008, the Ontario Government announced its Far North Planning Process. The Ontario government committed to protect more than 225 000 square kilometres, or more than half of the Northern Boreal lands, in an interconnected network of conservation lands, while seeking a balance between conservation and development. With Aboriginal communities, local land-use planning has also been initiated. The OGS is responsible to provide the geoscience information that will be considered during the planning. The OGS data collection strategy is to collect regional, "generation 1" framework geoscience data for the region by undertaking remote predictive surficial mapping or terrain analysis in three stages across the Far North (Barnett and Yeung, this volume); purchasing regional proprietary airborne geophysical survey data covering the Far North (Parker and Brown, this volume); conducting a technical gap analysis of priority areas (e.g., McFaulds Lake gap analysis, Parker and Brown, this volume); attempting to access confidential company geophysical and geochemical data under a confidentiality agreement so as to inform the construction of mineral potential maps; compiling assessment file mineral occurrence data, augmented by field visits, to enhance the mineral deposit inventory database; modifying the Provincially Significant Mineral Potential process to focus on a more qualitative approach; and flying new airborne geophysical surveys to fill in gap areas. Detailed feet-on-ground bedrock mapping will be considered in future years.

## Reforming and Modernizing Ontario's *Mining Act*

On October 21, 2009, the Act to amend the *Mining Act* (Bill 173) passed third reading in the legislature. Bill 173 includes a number of progressive provisions, including

- incorporating aboriginal consultation in mining legislation and regulations
- introducing a dispute-resolution process for aboriginal-related issues in mining
- requiring awareness training to obtain a prospector's licence
- strengthening environmental considerations during mineral exploration
- creating an efficient, made-in-Ontario map staking system
- protecting the property rights of private land owners who do not own their mineral rights

The OGS will be involved in the internal committee work to advise on the development of the policy initiatives and will assist in the consultations related to the finalization of the regulations.

## Multi-Jurisdictional – Ontario Collaborative Geoscience Initiatives

The OGS will continue its science collaboration with other jurisdictions on the planning and implementation of geoscience projects in Ontario. One multi-jurisdictional initiative under development is the geoscience documentation of the Hudson Platform rocks in Ontario—the rocks that lie adjacent to James Bay and Hudson Bay. Discussions continue with Manitoba, Nunavut, Quebec and the Government of Canada about the conceptual objectives and possible roles for each jurisdiction. A better understanding of this geology will provide new information to support the planning and resource development decisions related to the Far North Land-Use Planning Initiative. The Targeted Geoscience Initiative III (TGI-3) Abitibi project continues with Quebec and the Government of Canada (Parker and Brown, this volume).

## Groundwater Aquifer Mapping

The OGS is continuing its successful groundwater mapping initiative, which is largely based in southern Ontario. Strategic partnerships with Conservation Authorities, universities, and municipalities are helping to build a new, three-dimensional perspective of groundwater aquifers required to inform groundwater quantity and quality discussions and source-water protection decisions.

## Enhanced Geoscience Mandate Projects

New and expanded projects under the enhanced geoscience project mandate include collaboration with the Ministry of Environment on characterization of organic and inorganic composition of ground and surface water and associated sedimentary materials. A new energy-related geoscience project was initiated in southern Ontario to address the gas potential of sedimentary rocks (Béland Otis, this volume).

An exciting discovery of a potential ground-heat resource resulted from well-water geochemical studies. While still under investigation, the collaboration between the groundwater project team, the bedrock geology expert and the geophysical data expert will attempt to constrain the source of the ground heat (Hamilton and Freckelton, this volume).

Development continues on the Google Earth™ mapping service (“Google Earth”) as a scientific viewing tool, to help make our technical data more accessible to a very wide set of existing and new users.

## TECHNICAL GAP ANALYSIS

The technical geoscience gap analysis of northwestern Ontario was completed and the results influenced the implementation of bedrock mapping (Buse, Lewis and Magnus, this volume) and the planning of the Melchett Lake airborne geophysical survey. In addition, in the early summer 2009, the OGS conducted a technical gap analysis of the McFaulds Lake area. The results of these analyses will help guide the geological mapping program over the next 3 to 5 years.

## NEW ONTARIO GEOLOGICAL SURVEY STAFF

Several new staff joined the OGS or successfully competed for new positions within the OGS during the past year:

- Director's Office
  - Nadine Trödel (Project and Results Management Co-ordinator)
- Geoscience Laboratories
  - James Schweyer (Supervisor of Operations)
  - Marcus Burnham (Chief Scientist)
- Precambrian Geoscience Section
  - Sara Buse (Geoscientist)
  - David Lewis (Geoscientist)
  - Julie Chartrand (Geological Assistant)
  - Patrick Gervais (Drafter)
  - Jon Webb (Geological Assistant)
  - Tom Brown (Manager, Bedrock Mapping and Geophysics)
- Resident Geologist Program
  - Pierre Bousquet (District Support Geologist, Timmins)
  - Samantha MacDonald (District Support Geologist, Red Lake)
  - Genevieve Dorland (Cartographic Technologist, Northwest Region, Thunder Bay)
  - Hugh Lockwood (Regional Land Use Geologist, Northwest Region, Thunder Bay)
  - Ann Wilson (Mineral Deposit Compilation Geologist, Northeast Region, Timmins)
  - Dave Guindon (Regional Resident Geologist, Kirkland Lake)
- Sedimentary Geoscience Section
  - Catherine Béland Otis (Paleozoic Geologist – Energy)
  - Elizabeth Priebe (Co-ordinator of Research, Aquifer Mapping)
  - Andrea Marich (Surficial Geologist – Earth Studies)

## FUTURE

The OGS continues to

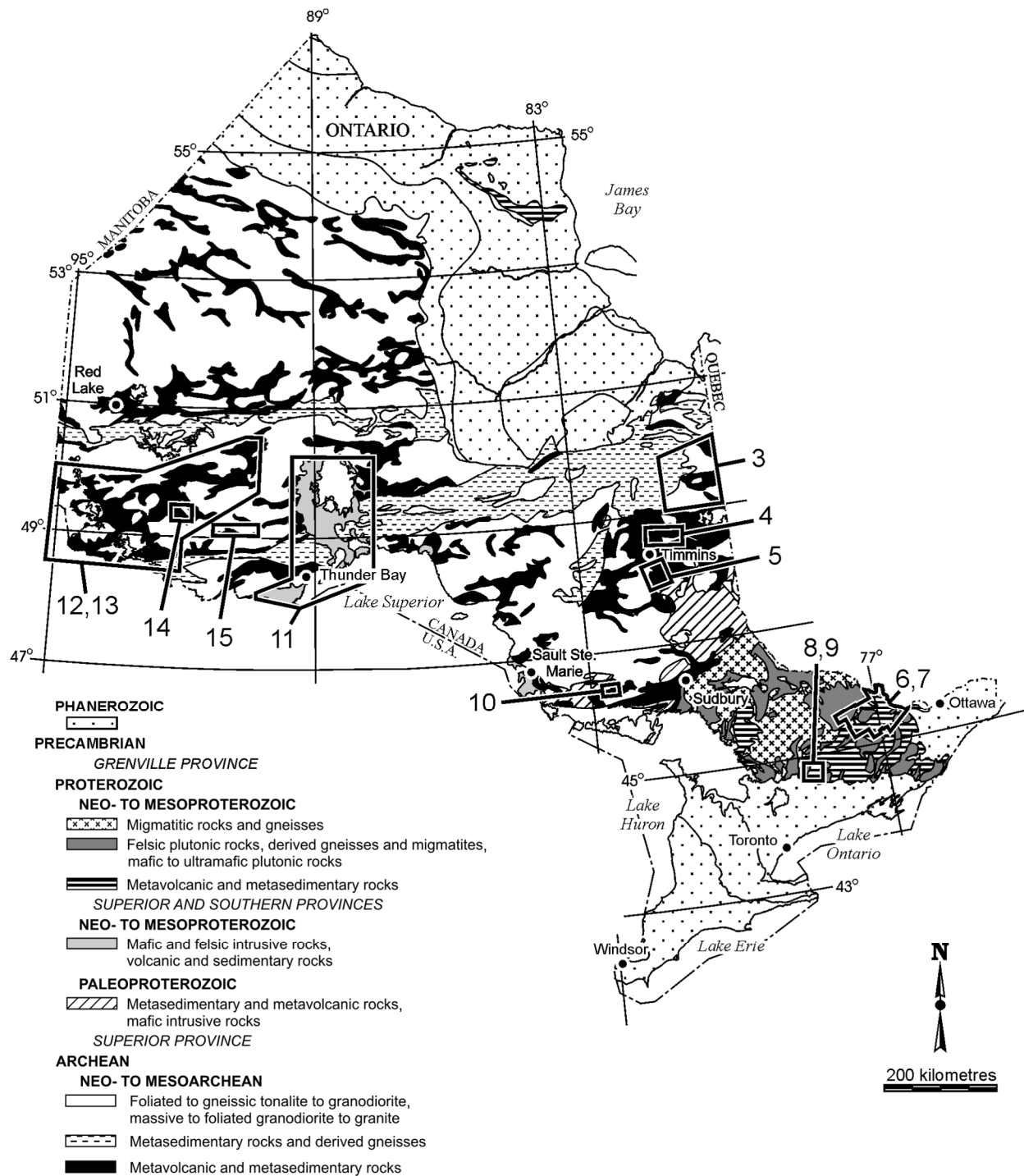
- implement aspects of the OGS Strategic Plan, consistent with the present priorities of the Ontario Government and the mandate of the Ministry of Northern Development, Mines and Forestry
- facilitate mineral and energy exploration through development and transfer of innovative ideas and methods
- facilitate balanced land-use planning through the provision of modern geoscience data and the knowledge vested in the OGS staff
- identify geological features relevant to Ontario's public health and safety
- publish and market information on Ontario's landmass and 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 use Google Earth™, which show great promise as the medium to broaden the access and awareness of OGS geoscience goods and services to both traditional and non-traditional users

Public geoscience plays an important role in helping support public policy decision-makers, investors, and other users of the near surface of the Earth. Societal needs are increasingly complex and require a sound and objective understanding and application of geoscience to help assess and frame the complex options available. The OGS is working hard to supply the required data and geoscience knowledge needed to support those broad but fundamental decisions.

The preliminary results of our geoscience activities, reported in this volume, are indications of the efforts being made to help ensure the relevant geoscience data and methods are available to be considered by those addressing the public policy and societal issues.

# **Precambrian Geoscience Section**

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Location of Precambrian Geoscience Section projects for 2009–2010. Numbers correspond to article numbers.

## 2. Precambrian Geoscience Section: Program and Project Overview

J.R. Parker<sup>1</sup> and T. Brown<sup>1</sup>

<sup>1</sup>Precambrian Geoscience Section, Ontario Geological Survey

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### GOAL AND RESPONSIBILITY OF THE PRECAMBRIAN GEOSCIENCE SECTION

The goal of the Precambrian Geoscience Section (PGS) is to improve the understanding of Precambrian geology and metallogeny of Ontario and to convey this knowledge to clients through multi-year, multidisciplinary geoscience projects that address critical geoscience problems in key geographic areas. These studies may be delivered as part of the PGS core bedrock mapping function or through collaborative partnerships.

PGS is responsible for

- mapping of Ontario's Precambrian bedrock and understanding of various mineral deposit settings;
- regional gravity, magnetic and electromagnetic geophysical data and derivative products in support of the bedrock mapping program.

### PRECAMBRIAN GEOSCIENCE SECTION CORE FUNCTIONS

The program direction and strategic thrusts of the PGS address the results-based plan and core business of the Ministry of Northern Development, Mines and Forestry. Strategic thrusts (Table 2.1) are achieved through a variety of initiatives that are built on one or more projects (Table 2.2). Therefore, project development, selection, planning and implementation are based on the strategic thrusts and initiatives in order to achieve alignment of individual projects with Ministry priorities.

The fundamental core functions of PGS projects are to

1. provide geoscience maps, reports, data, technical talks and posters, new concepts and ideas and client consultations; and
2. provide regional airborne geophysical data, derivative products, and concepts and ideas based on those geophysical data to support the bedrock mapping program.

The PGS supported 40 active projects during the 2009–2010 fiscal year including 26 active core projects (*see* Table 2.2) and 14 active collaborative projects, which include 10 projects with the Geological Survey of Canada (Table 2.3).

In 2009, the PGS produced 11 Preliminary Maps, 2 Open File Reports and 8 Miscellaneous Releases—Data (MRDs), 5 Geophysical Data Sets and 62 airborne geophysical magnetic and electromagnetic survey maps as of December 2009. The PGS staff presented approximately 25 technical talks and 20 posters at various geoscience forums and meetings throughout the year.

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*Summary of Field Work and Other Activities 2009,  
Ontario Geological Survey, Open File Report 6240, p.2-1 to 2-16.*

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Table 2.1. Strategic Thrusts of the Precambrian Geoscience Section: 2009–2010.

Strategic Thrust	Thrust Objective	Initiatives To Achieve Thrust	Priority Action
1. Understand the geology and metallogeny of high mineral potential areas in the Superior, Southern and Grenville provinces.	Improve understanding of the tectonic and metallogenic evolution and mineral potential of the Superior, Grenville, and Southern provinces by integration of systematic bedrock mapping, mineral deposit studies, geological and geophysical interpretation and compilation at scales of 1:20 000, 1:50 000, 1:100 000, 1:250 000 and 1:2 000 000.	Provincial Initiatives	<p>Provincial Resource Allocation:</p> <p>Undertake bedrock mapping and compilation augmented with mineral deposit data and geophysical interpretation:</p> <ul style="list-style-type: none"> <li>• <i>Non-frontier</i> areas and mining camps at scales of 1:20 000 in English and Zavitz and Hutt and Semple townships, Abitibi Subprovince;</li> <li>• <i>Non-frontier</i> 1:100 000 scale bedrock geology compilation and geochronology in the Ramsey–Algoma region, Abitibi Subprovince;</li> <li>• <i>Non-frontier</i> 1:100 000 scale bedrock geology compilation and geochronology in the Detour–Burntbrush lakes region, Abitibi Subprovince;</li> <li>• <i>Non-frontier</i> 1:20 000 scale bedrock mapping in the Bending Lake greenstone belt, Wabigoon Subprovince;</li> <li>• <i>Non-frontier</i> 1:20 000 scale bedrock mapping in the Lumby Lake greenstone belt, Wabigoon Subprovince;</li> <li>• <i>Non-frontier</i> 1:100 000 scale bedrock geology compilation and geochronology in the western Wabigoon Subprovince;</li> <li>• <i>Non-frontier</i> 1:20 000 scale mapping in the Elliot Lake area, Huronian Supergroup and Abitibi Subprovince.</li> </ul>
		Far North Initiative	<p><u>Far North Land Use Planning Initiative:</u></p> <p>Undertake frontier bedrock mapping, compilation and airborne geophysical data acquisition as part of the Far North Land Use Planning Initiative:</p> <ul style="list-style-type: none"> <li>• Conduct geoscience gap analysis meeting for the McFaulds Lake region;</li> <li>• Conduct reconnaissance bedrock mapping and sampling in the Sutton Inliers;</li> <li>• Conduct “Request for Data” to purchase proprietary airborne geophysical data;</li> <li>• Conduct regional airborne magnetic geophysical survey of the Melchett Lake region;</li> <li>• Conduct 1:1 000 000 scale regional bedrock geology and mineral deposit inventory (MDI) compilation for the Far North;</li> <li>• Provide Senior Geoscientist (Trowell) for participation on the Far North Information and Knowledge Management Working Group.</li> </ul>

Table 2.1. continued

Strategic Thrust	Thrust Objective	Initiatives To Achieve Thrust	Priority Action
1. (continued)	Abitibi Initiative	<p><u>Abitibi Initiative:</u></p> <p>a) <i>Abitibi Targeted Geoscience Initiative:</i></p> <p>In collaboration with the Geological Survey of Canada, Géologie Québec, industry and academia, participate in the Targeted Geoscience Initiative program:</p> <ul style="list-style-type: none"> <li>• In-kind support by committing a portion of the PGS core bedrock mapping program to the Abitibi greenstone belt (Ayer, Berger, Houllé, Préfontaine, Duguet, Trowell, Chartrand);</li> <li>• Deliver and participate in collaborative geoscience projects.</li> </ul> <p>b) <i>Discover Abitibi:</i></p> <p>In collaboration with the Timmins Economic Development Corporation, academia and industry, participate in and provide support to the planning stage of the Discover Abitibi program:</p> <ul style="list-style-type: none"> <li>• Provide Senior Geoscientist (Ayer) for participation on the Discover Abitibi Technical Committee;</li> <li>• Provide Geophysicist (Rainsford) for technical support for pre-publication of airborne geophysical data.</li> </ul>	<p><u>Abitibi Initiative:</u></p> <p>a) <i>Abitibi Targeted Geoscience Initiative:</i></p> <p>In collaboration with the Geological Survey of Canada, Géologie Québec, industry and academia, participate in the Targeted Geoscience Initiative program:</p> <ul style="list-style-type: none"> <li>• In-kind support by committing a portion of the PGS core bedrock mapping program to the Abitibi greenstone belt (Ayer, Berger, Houllé, Préfontaine, Duguet, Trowell, Chartrand);</li> <li>• Deliver and participate in collaborative geoscience projects.</li> </ul> <p>b) <i>Discover Abitibi:</i></p> <p>In collaboration with the Timmins Economic Development Corporation, academia and industry, participate in and provide support to the planning stage of the Discover Abitibi program:</p> <ul style="list-style-type: none"> <li>• Provide Senior Geoscientist (Ayer) for participation on the Discover Abitibi Technical Committee;</li> <li>• Provide Geophysicist (Rainsford) for technical support for pre-publication of airborne geophysical data.</li> </ul>
	Proterozoic Initiative	<p><u>Proterozoic Initiative:</u></p> <p>a) <i>Geology of Cavendish Township:</i></p> <p>Complete map, report and data sets for publication.</p> <p>b) <i>Geology of the Elliot Lake area:</i></p> <p>Conduct bedrock mapping at 1:20 000 scale to better understand the stratigraphy, structure and setting of uranium mineralization in the area.</p> <p>c) <i>Compilation of the East Bull Lake and Agnew intrusions:</i></p> <p>Complete map and data sets for publication.</p> <p>d) <i>Midcontinent Rift compilation:</i></p> <p>A continuation of a compilation of the geology of the Midcontinent Rift system conducted in collaboration with the United States Geological Survey and the Minnesota Geological Survey.</p> <p>e) <i>Geological, paleomagnetic, geochemical and geochronological studies of Mesoproterozoic Midcontinent Rift-related mafic intrusions:</i></p> <p>Conduct reconnaissance sampling of intrusions near Thunder Bay to characterize their geochemistry and assess their mineral potential.</p> <p>f) <i>Assessment of zinc potential in marbles:</i></p> <p>Reconnaissance sampling of marbles in the Renfrew region to assess zinc potential.</p>	<p><u>Proterozoic Initiative:</u></p> <p>a) <i>Geology of Cavendish Township:</i></p> <p>Complete map, report and data sets for publication.</p> <p>b) <i>Geology of the Elliot Lake area:</i></p> <p>Conduct bedrock mapping at 1:20 000 scale to better understand the stratigraphy, structure and setting of uranium mineralization in the area.</p> <p>c) <i>Compilation of the East Bull Lake and Agnew intrusions:</i></p> <p>Complete map and data sets for publication.</p> <p>d) <i>Midcontinent Rift compilation:</i></p> <p>A continuation of a compilation of the geology of the Midcontinent Rift system conducted in collaboration with the United States Geological Survey and the Minnesota Geological Survey.</p> <p>e) <i>Geological, paleomagnetic, geochemical and geochronological studies of Mesoproterozoic Midcontinent Rift-related mafic intrusions:</i></p> <p>Conduct reconnaissance sampling of intrusions near Thunder Bay to characterize their geochemistry and assess their mineral potential.</p> <p>f) <i>Assessment of zinc potential in marbles:</i></p> <p>Reconnaissance sampling of marbles in the Renfrew region to assess zinc potential.</p>

Table 2.1. continued

Strategic Thrust	Thrust Objective	Initiatives To Achieve Thrust	Priority Action
1. (continued)	Metallogeny and Geology of Northwest Ontario	Metallogeny and Geology of Northwest Ontario	<p><u>Metallogeny and Geology of Northwest Ontario:</u></p> <p>a) <i>Geology of the central Wabigoon Subprovince:</i> Complete synoptic report and final 1:250 000 scale bedrock compilation map.</p> <p>b) <i>Geology of the Bending Lake greenstone belt:</i> Conduct bedrock mapping at 1:20 000 scale to better understand the geology and mineralization in the area</p> <p>c) <i>Western Wabigoon Synthesis:</i> Conduct 1:100 000 scale bedrock geology compilation and synthesis of the western Wabigoon Subprovince.</p> <p>d) <i>Atikokan Mineral Development Initiative:</i> In collaboration with the Atikokan Economic Development Corporation, the Ontario Prospectors Association, academia and industry, participate in and provide in-kind support to the Atikokan Mineral Development Initiative:</p> <ul style="list-style-type: none"> <li>• Provide Geoscientists (Stone, Rainsford) for participation on the Atikokan Mineral Development Science Committee;</li> <li>• Provided Geophysicist (Rainsford) for technical assistance on pre-publication of airborne geophysical data;</li> <li>• Completed and published a high-resolution airborne magnetic and electromagnetic geophysical survey at Mine Centre in the Atikokan region;</li> <li>• Conduct bedrock mapping at 1:20 000 scale to better understand the structure, stratigraphy and mineralization of the Lumby Lake greenstone belt.</li> </ul> <p>e) <i>Greenstone Mineral Development Initiative:</i> Provide Senior Geoscientist (Stott) for technical support.</p>
	Initiatives with GSC	<u>Collaborative Initiatives with Geological Survey of Canada (GSC):</u>	<p>a) <i>Abitibi Targeted Geoscience Initiative:</i> In collaboration with the Geological Survey of Canada, Géologie Québec, industry and academia, participate in the Targeted Geoscience Initiative program.</p>

Table 2.1. continued

Strategic Thrust	Thrust Objective	Initiatives To Achieve Thrust	Priority Action
2. Understand and inventory provincial-scale relationships, settings and descriptive data sets of commodities or deposit types currently of interest to the mineral exploration industry.	<p>Improve the understanding of, and mineral potential for, rocks that may contain economic concentrations of</p> <ul style="list-style-type: none"> <li>- diamonds;</li> <li>- rare-metal and petalite-bearing pegmatites;</li> <li>- Ni-Cu-PGE;</li> <li>- gold;</li> <li>- VMS-associated copper-zinc mineralization; and</li> <li>- metallic mineralization related to felsic magmatism</li> </ul>	<ul style="list-style-type: none"> <li>- Provincial-scale Metallogenic Inventory</li> </ul>	<p>a) Document the distribution of, regional settings, and characteristics of</p> <ul style="list-style-type: none"> <li>- Mineralized, intermediate to felsic plutonic systems (Beakhouse);</li> <li>- Evolved (F1- to FIII-type) felsic metavolcanic rocks across the Superior Province (Berger);</li> </ul> <p>by conducting ongoing mapping and office-based compilations and inventories supplemented by field work (e.g., sampling and localized bedrock mapping at various scales).</p> <p>b) Maintain geochronology database for Ontario (Easton).</p>
3. Improve knowledge of, and access to, geophysical information by providing an effective and efficient information management system through the identification, recovery, (re-) formatting, organization and delivery of all available OGS and proprietary geophysical information; and provide derivative geophysical products, concepts and ideas, based on those geophysical data, to support the bedrock mapping program.	<p>Integrate regional geophysics into core business bedrock mapping projects.</p> <p>Improve client awareness of, and access to, all OGS and proprietary geophysical data sets.</p>	<p>Geophysics and Bedrock Mapping Integration Initiative</p>	<p>Provide ongoing support of bedrock mapping and compilation projects.</p> <p>Develop new approaches, procedures and methodologies to integrate and establish geophysical component of bedrock mapping projects.</p> <p>Assess and apply new technologies for processing, interpreting and presenting geophysical data (i.e., geophysical inversion and 3D visualization software).</p> <p>Maintain the Geophysical Atlas containing a graphical index of all available airborne geophysical survey information describing Ontario.</p> <p>Maintain an on-line repository (master archive) of all available airborne geophysical survey information, which will be used to seed all publications of geophysical data and which will be maintained by the OGS geophysicist.</p> <p>Acquire, process and publish proprietary, multi-parameter, regional, airborne geophysical survey data.</p> <p>Provide support in the design and delivery of regional airborne surveys as part of core program and community-driven geosciences initiatives (e.g., Mine Centre, Chatham Sag, Shining Tree, Detour Lake, Burnbush Lake, Lumby-Finlayson lakes, Marmion Lake and Melchett Lake area surveys).</p> <p>Continue the development, ongoing maintenance and publication of a rock properties database as part of OGS bedrock mapping projects, i.e., recover rock density data; magnetic susceptibility data; specific gravity data; establish data standards, storage format and plan.</p>
		<p>Geophysics and Rock Properties Data Set Initiative</p>	

Table 2.1. continued

Strategic Thrust	Thrust Objective	Initiatives To Achieve Thrust	Priority Action
4. Implement program support practices and instruments to address and refine the PGS core program, the human resource strategy, digital data standards and program management practices.	<p>Implement human resource strategy by focussing on succession plans for critical positions and developing a PGS Learning Plan as required by Management Board Secretariat.</p> <p>Complete Management Board Secretariat (MBS) mandated Program Review of geoscience program.</p> <p>Continue to implement project management and impact assessment practices.</p> <p>Provide staff with the Information Technology (IT) tools and operational manuals required to deliver the 2009 summer field projects.</p>	<p>Strategic hiring and mentoring initiative to anticipate retirements of staff and loss of corporate and technical knowledge</p> <p>Support and Program Management Practices Initiative</p> <ul style="list-style-type: none"> <li>- Project and Results Management Initiative</li> <li>- Methods Development and Data Standards Initiative</li> </ul>	<p>Address HR issues:</p> <ul style="list-style-type: none"> <li>• Develop and implement staff technical and other training plans;</li> <li>• Maintain the OGS Health and Safety Manual;</li> <li>• Hire and train “strategically” to anticipate retirement and loss of corporate and technical knowledge;</li> <li>• Participate in the OGS Branch review of the functions and responsibilities of the Geoscientist classification.</li> </ul> <p>Continue to implement and maintain project management tools and practices, including</p> <ul style="list-style-type: none"> <li>• Project planning processes;</li> <li>• Report on PGS performance measures.</li> </ul> <p>Continue development of a new process for collecting and digitizing field observations to streamline the workflow process for producing hard-copy maps and digital data sets and creating a common archival format:</p> <ul style="list-style-type: none"> <li>• Develop software and hardware solutions for field data collection and digitizing of geological observations using ArcPad®;</li> <li>• Fully integrate new solutions with current GIS data workflow;</li> <li>• Work toward new data standards for PGS and facilitate production of hard-copy maps and digital data;</li> <li>• Develop a consistent rock legend for bedrock geology maps through the Common Legend Committee;</li> <li>• Purchase software and hardware to be used for core program, pilot studies, methods development, and standards projects.</li> </ul>
			<p>Apply drafting and GIS functions in support of the PGS mapping program by providing staff with</p> <ul style="list-style-type: none"> <li>• ArcGIS® training for use in ongoing projects;</li> <li>• Operational field computers and peripheral equipment;</li> <li>• Up-to-date digital mapping manual;</li> <li>• Up-to-date mapping project manual.</li> </ul>

Table 2.1. continued

Strategic Thrust	Thrust Objective	Initiatives To Achieve Thrust	Priority Action
5. Manage and maintain client, stakeholder, and First Nation relationships.	Contribute to awareness of external and internal clients and stakeholders and other ministries and governments, regarding the value of PGS geoscience program, have a direct means to communicate with the PGS geoscience program, and manage PGS-related issues at as early a stage as possible.	<p>External Committees</p> <p>Internal Government committees</p> <p>Work with OGS Director's Office to maintain relationships and exchange technical information with First Nation communities and organizations located in geographic areas where PGS has a geoscience program interest between now and 15 years into the future.</p>	<p>Client and stakeholder meetings:</p> <p>Represent Mines and Minerals Division (MMD), OGS, and PGS on/at</p> <ul style="list-style-type: none"> <li>- North American Commission on Stratigraphic Nomenclature</li> <li>- Targeted Geoscience Initiative III Abitibi Project</li> <li>- Atikokan Mineral Development Initiative Science Committee</li> <li>- Discover Abitibi Technical Committee</li> <li>- Far North Information and Knowledge Management Working Group</li> <li>- MNDMF Management Health &amp; Safety Committee</li> <li>- Regional client association meetings</li> <li>- Thesis committees and adjunct professorships at universities</li> <li>- Prospectors and Developers Association of Canada (PDAC) Student-Industry Mineral Exploration Workshop Committee</li> <li>- PGS program-level discussions with other governments.</li> </ul>

Table 2.2. Precambrian Geoscience Section core projects, 2009–2010.

Initiative	Project	Project Goal	Project Status
Abitibi Initiative	Discover Abitibi	Participation in Technical Committee and provision of technical support for regional airborne geophysical surveys (e.g., Detour Lake, Burntbrush Lake, Shining Tree areas)	Ongoing; airborne geophysical surveys published in 2009
	Ramsey-Algonia compilation	1:100 000 scale bedrock compilation map	Map and data to be published in 2010
	Geochemistry of Ni-Cu-(PGE) ores in the Abitibi greenstone belt	Compile a database of Ni-Cu-PGE ore compositions from the Abitibi	Ongoing; database is presently being compiled
Proterozoic Initiative	Geology and mineral potential of Cavendish Township, Grenville Province	1:20 000 scale bedrock mapping	Map to be published in 2010
	Geology of the Elliot Lake area	1:20 000 scale bedrock mapping	Map to be published in 2010
	Assessment of zinc potential in marbles	Reconnaissance sampling project; collect and compile data	Miscellaneous Release—Data to be published in 2010

Table 2.2. continued

Initiative	Project	Project Goal	Project Status	
Metallogeny and Geology of Northwest Ontario	Atikokan Mineral Development Initiative	Participation in Science Committee and provision of technical support for regional airborne geophysical surveys (e.g., Lumby–Finlayson lakes, Marmion Lake areas)	Ongoing; airborne geophysical surveys published in 2009	
	Geology of the central Wabigoon Subprovince: bedrock compilation of the Atikokan area	1:250 000 scale compilation	Map and report to be published in April 2010	
	Geology of the Bending Lake greenstone belt	1:20 000 scale bedrock mapping of the Bending Lake area	Map to be published in 2010	
	Western Wabigoon Synthesis	1:100 000 scale bedrock and geoscience data compilation	First compilation map to be published in 2010	
	Geology and mineral potential of the Shebandowan greenstone belt	1:20 000 scale mapping in the Hamlin and Wye lakes area	Map to be published in December 2009	
	Geology and mineral potential of the Caribou Lake greenstone belt	1:50 000 scale bedrock mapping of the Caribou Lake greenstone belt	Map to be published in December 2009	
	Lake of the Woods compilation map	Legacy release of 1:50 000 compilation of previously published maps	Map to be published in 2010	
	Distribution of gold with respect to lithologies, metamorphic facies and strain state in the Beardmore–Geraldton greenstone belt	Legacy release of Open File Report and Miscellaneous Release—Data	Open File Report and Miscellaneous Release—Data to be published in December 2009	
	Provincial-Scale Metallogenic Inventory Initiative	Distribution of potentially volcanogenic massive sulphide (VMS)-productive felsic metavolcanic rocks	Compile locations of FI-, FII- and FIII-type rhyolites across Ontario	Ongoing; database is presently being compiled
		Characteristics of mineralized intermediate to felsic plutonic systems	Gather and compile information on barren and mineralized felsic plutons across Ontario	Ongoing compilation; report on work in the Abitibi Subprovince to be published in 2010
Update and maintain geochronology database		Maintain up-to-date geochronology database for Ontario	Ongoing; database is presently being updated for publication	
Far North Initiative	Bedrock and Mineral Deposit Inventory compilation of the Far North	1:1 000 000 scale compilation	Map and Miscellaneous Release—Data to be published in December 2009	
	Reconnaissance of the Sutton Inliers	Reconnaissance mapping and sampling.	<i>Summary of Field Work</i> article and Miscellaneous Release—Data to be published in December 2010	

Table 2.2. continued

<b>Initiative</b>	<b>Project</b>	<b>Project Goal</b>	<b>Project Status</b>
Geophysics and Bedrock Mapping Integration Initiative	Geophysics integration with bedrock mapping projects	Integrate geophysics into the PGS bedrock mapping program	Ongoing
	Airborne magnetic geophysical survey of the Chatham Sag region	Data collected in winter–spring 2009	Maps and geophysical data set published October 2009
	Airborne magnetic and electromagnetic geophysical survey of the Mine Centre area	Data collected in winter–spring 2008–2009	Maps and geophysical data set published October 2009
	Airborne magnetic geophysical survey of the Melchett Lake region	Data collection scheduled for 2009–2010 fiscal year; airborne magnetic geophysical survey of 13 479 square kilometres	Maps and Geophysical Data Set anticipated to be published in 2010
Geophysics and Rock Properties Data Set Initiative	Project Management and QA/QC of airborne geophysical surveys during fiscal 2008–2009	Manage and QA/QC geophysical data for 2 regional geophysical surveys in Ontario; contracted to Paterson, Grant & Watson Ltd.	Completed in summer 2009
	Purchase and publication of proprietary airborne geophysical data	Eleven airborne geophysical survey data sets purchased as of October 2009	Maps and Geophysical Data Sets to be published in 2010
	Rock properties project	Collect and archive rock properties data	Ongoing; database to be published in 2010
Support and Program Management Practices Initiative	Improving OGS Archives	Improve archives database and archiving processes	Ongoing
	Strategic Hiring and Mentoring Initiative	Managing loss of staff, corporate and technical knowledge	Ongoing
Methods Development and Data Standards Initiative	Integrated solution for field data collection and processing	Develop recruitment strategies to hire and train “strategically” to anticipate staff retirements	Ongoing
	Common Legend for Ontario bedrock geology	Establish new methods for digital collection of geological data in the field; development of data model for mapping projects	Ongoing
	Digital map standards throughout Ontario	Develop revised and consistent rock legend for bedrock geology maps	Ongoing
External and Internal Committees; OGS Advisory Board; First Nations	Ongoing maintenance of relationships and exchange of technical information with clients, stakeholders and First Nations	Standardize digital map standards	Ongoing
		Ensure external and internal clients and stakeholders are aware of the value of the PGS geoscience program	Ongoing

Table 2.3. Precambrian Geoscience Section collaborative initiatives, 2009–2010.

Initiative	Project	Project Collaborator(s)	Project Progress
Proterozoic Initiative	Midcontinent Rift compilation	United States Geological Survey, Minnesota Geological Survey	Ongoing
	Geological, paleomagnetic, geochemical and geochronological studies of Mesoproterozoic Midcontinent Rift-related mafic intrusions near Thunder Bay	Lakehead University	Ongoing; Miscellaneous Release—Data published in October 2009 and <i>Summary of Field Work</i> article in December 2009
	East Bull Lake intrusion and Agnew intrusion 1:50 000 scale geological compilation map	Cambrian College, Laurentian University	Map is being finalized and will be published in 2010
Metallogeny and Geology of Northwest Ontario	1:20 000 scale bedrock mapping of the Lumby Lake greenstone belt	Atikokan Mineral Development Initiative	Map and Miscellaneous Release—Data to be published in April 2010
Collaborative Projects with the GSC:	1:100 000 scale bedrock compilation of the Detour–Burntush lakes area	Geological Survey of Canada, industry	Map and Miscellaneous Release—Data published in 2009
Targeted Geoscience Initiative III (TGI-3) Abitibi Project and Deep Search Project	Bedrock mapping of the Kidd–Munro assemblage	Geological Survey of Canada, University of Ottawa, Mineral Exploration Research Centre (MERC)—Laurentian University, industry	1:100 000 scale compilation of Kidd–Munro assemblage; map and Miscellaneous Release—Data to be published in 2010
	Bedrock mapping in the Bartlett Dome area south of Timmins	Geological Survey of Canada, industry	1:20 000 scale maps of English–Zavitz and Hutt–Sample townships to be published in 2010
	Geochemical compilation and process recognition in the Abitibi Subprovince, Quebec–Ontario	Geological Survey of Canada, Géologie Québec	Ongoing
	Acquisition of new samples for U/Pb geochronology in the Abitibi Subprovince	Geological Survey of Canada, Géologie Québec	Ongoing
	Regional reconnaissance for organized paleohydrothermal systems in the Kidd–Munro assemblage and the Blake River Group	Geological Survey of Canada	Ongoing
	Structural and stratigraphic investigations of the Kidd–Munro assemblage	Geological Survey of Canada	Ongoing
	Exhalative vectors toward base metal mineralization	Geological Survey of Canada, industry	Ongoing
	Physical volcanology and chemistry of FIII-type rhyolites in the Kidd–Munro assemblage	Geological Survey of Canada, University of Ottawa	MSc thesis study
	Characterization of the mineralization and alteration at the Potter Mine in the Kidd–Munro assemblage	Millstream Mines Ltd. Geological Survey of Canada, MERC—Laurentian University	MSc thesis study

## PROGRAM DIRECTION: STRATEGIC THRUSTS

### Core Bedrock Mapping and Geophysics Program

The PGS Strategic Thrusts (*see* Table 2.1) are derived from the Ministry of Northern Development, Mines and Forestry business goals as articulated in the OGS Strategic Plan.

The purpose of the PGS Strategic Thrusts 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; support sustainable development and effective land-use planning; attract new mineral investment; build new partnerships with Aboriginal communities, private sector and federal government; and collaborate with other ministries on mutual initiatives.

The PGS program is organized into 5 technical or administrative Strategic Thrusts:

1. Understand the geology and metallogeny of high mineral potential areas in the Superior, Southern and Grenville provinces;
2. Understand and inventory provincial-scale relationships, settings and descriptive data sets of commodities or mineral deposit types that are currently of interest to the mineral exploration industry (e.g., potential diamond-bearing rocks, gold mineralization, nickel-copper-platinum group element (PGE) mineralization and volcanogenic massive sulphide (VMS) mineralization) or may be of interest in the future;
3. Improve knowledge of, and access to, regional geophysical data by providing an effective and efficient data management system through the identification, recovery, (re-)formatting, organization and delivery of all available OGS and proprietary geophysical information; and provide derivative geophysical products, concepts and ideas, based on those geophysical data, to support the bedrock mapping program;
4. Implement program support practices and instruments to address and refine the PGS core program, the human resource strategy, digital data standards, measurement of program results and program management practices;
5. Develop and manage client and stakeholder relationships by providing a liaison role, representation, or support on behalf of the PGS on client committees, regional client association meetings, inter-Ministry committees and formal or informal working groups; and committees or working groups associated with professional or learned associations. Maintain relationships and exchange technical information with First Nation communities and organizations located in geographic areas where PGS specifically has a geoscience program interest between the present and 15 years into the future.

These strategic thrusts are addressed through a series of initiatives, built upon one or more projects. The purpose of the strategic thrusts is to focus PGS staff and resources in key geological areas to address the priorities and needs of the initiative. In addition, PGS participates in several collaborative projects to complement existing PGS staff skills and capacity and to expand the amount of geoscience data that describe Ontario. Collaborative projects are an important means to extend scarce government resources and to capitalize on resources and expertise available in other government geological surveys, universities or industry.

## **PROJECT PLANNING, MANAGEMENT, AND CONSULTATION PROCESS**

The PGS management and staff conducted planning and project management processes and practices to deliver 40 geoscience projects conducted by core staff and in collaboration with partners. Information required to describe projects, monitor and adjust progress, and assess their impact on the minerals industry is collected and analyzed to assess achievement of program goals.

To formulate and discuss project plans for summer of 2009 and to begin development of summer 2009 project plans, PGS was involved in several consultations with regional client associations:

- May 2009: Porcupine Prospectors and Developers Association, Timmins; Sault District Prospectors Association, Sault Ste. Marie; Sudbury Prospectors and Developers Association, Sudbury
- June 2009: Northwestern Ontario Prospectors Association, Thunder Bay.

In July 2009, the Ontario Geological Survey conducted a Geoscience Gap Analysis meeting for the McFaulds Lake region, in the Far North of Ontario, to identify geoscience gaps, identify and prioritize industry needs, and identify possible OGS project designs that may meet those needs. The meeting was attended by representatives from 18 companies currently working in the McFaulds Lake region. Results of the meeting will be considered during the OGS Branch project planning cycle with implementation of some projects in 2010–2011.

## **NEW PROJECTS**

The following new technical initiatives will most likely be operational and will require resources of the PGS during the 2009–2010 fiscal year:

- Geo-Mapping for Energy and Minerals (GEM) (PGS staff are participating in this federal initiative, which is currently in the proposal/planning stage).

## **COMMUNITY-GUIDED GEOSCIENCE**

The Atikokan Mineral Development Initiative (AMDI) is a multi-year geoscience study in the Atikokan region that is addressing geoscience problems identified by the mineral industry as critical to advance the next generation of mineral exploration in the region, to reduce exploration risk, to enhance the likelihood of discovering a mine, and to increase immediate and future resource-based economic development in the region. The AMDI received \$1 million in funding from the Northern Ontario Heritage Fund Corporation, \$100 000 from the Town of Atikokan and \$370 000 from FedNor. The initiative is managed by the Ontario Prospectors Association. In 2009, the AMDI completed a high-resolution airborne magnetometer geophysical survey over the Marmion batholith.

In-kind support by PGS to the AMDI consisted of technical assistance in the preparation of Request for Proposals (RFPs) for airborne geophysical surveys; technical assistance in the pre-publication preparation of the airborne geophysical data; technical assistance in the preparation of a Request for Tender (RFT) for geochronological work; participation of staff (D. Stone, D.R.B. Rainsford) on the AMDI Science Committee; conducting a high-resolution airborne magnetometer and electromagnetic survey over Mine Centre; and conducting bedrock mapping of the Lumby Lake greenstone belt with the support of AMDI (Buse, Lewis and Magnus, this volume).

In-kind support by PGS to the Discover Abitibi Initiative (DAI) consists of the participation of J.A. Ayer on the DAI Technical Committee and providing technical assistance on RFPs and publications for various geoscience projects including airborne geophysical surveys.

In-kind support by PGS to the Greenstone Mineral Development Initiative consists of the participation of G.M. Stott in providing technical assistance. The initiative consists of three-dimensional (3D) digitization of historic gold mines and compilation of geoscience and mineral exploration data.

## PRECAMBRIAN GEOSCIENCE SECTION INITIATIVES

Precambrian Geoscience Section initiatives are based on geographic or functional groupings and are made up of 1) team initiatives (i.e., Abitibi Initiative) consisting of individual projects that are designed to meet an overall goal; 2) inter-jurisdictional team initiatives, such as the Targeted Geoscience Initiative III Abitibi project, that consist of individual and joint Ontario Geological Survey (OGS), Géologie Québec (MRNF) and Geological Survey of Canada (GSC) projects that are also designed to meet an overall goal or objective; and 3) individual, focussed projects. The major initiatives of the PGS are subdivided into 6 broad categories outlined below and in Table 3.2 and Table 3.3.

Initiatives that involve collaborative project agreements with the Geological Survey of Canada (GSC):

- Targeted Geoscience Initiative III (TGI-3) Abitibi project and Deep Search project.

Initiatives involving provincial-scale metallogenic compilation and inventory studies:

- Documentation of specific types of mineralization;
- Inventories of various tectonic settings relevant to mineral exploration.

Initiatives based on geographic area:

- Abitibi initiative;
- Metallogeny and geology of northwest Ontario;
- Proterozoic initiative.

Initiatives involving support of the PGS program:

- Support to program management practices;
- Project and results management;
- Methods development and data standards;
- Strategic hiring and mentoring.

Initiatives involving geophysical projects:

- Geophysics and bedrock mapping integration initiative;
- Geophysics and rock properties data set initiative.

Initiatives that develop and manage client, stakeholder and First Nation relationships:

- External and internal committees;
- Regional associations;
- Maintaining relationships and exchanging technical information with First Nation communities.

## **Collaborative Projects with the Geological Survey of Canada**

2009 is the last year of the Targeted Geoscience Initiative III (TGI-3) which is a five-year federal geoscience program to sustain base metal reserves associated with established, base metal mining communities in Canada. The TGI-3 Abitibi and Deep Search projects are a multidisciplinary, fully integrated and jointly delivered provincial–federal geoscientific effort with participation from industry and universities that is focussed on vulnerable established mining communities of the Abitibi in Quebec and Ontario. The Geological Survey of Canada (GSC), Géologie Québec, Ontario Geological Survey, industry and academia have been conducting collaborative geoscience projects throughout the Abitibi greenstone belt.

In the Ontario part of the Abitibi Subprovince, the focus of joint OGS–GSC TGI-3 projects has been in the Timmins and Kirkland Lake regions on the Kidd–Munro assemblage (Berger, Houlé and Diné, this volume); the Tisdale assemblage in the Bartlett Dome area (Préfontaine et al., this volume) and the Detour–Burntbush lakes area (Ayer, Trowell and Dubé, this volume). Presently, all PGS geoscience projects in the Abitibi greenstone belt represent OGS in-kind contributions to TGI-3 Abitibi. The Kidd–Munro project is in the final write-up stage with final products scheduled for release in 2010. Other projects, such as bedrock mapping in the Bartlett Dome area, will continue as a core PGS project.

## **Collaborative Project with the Beijing SHRIMP Centre, Chinese Academy of Geological Sciences**

In 2007, the PGS commenced a pilot project agreement with the Beijing SHRIMP (sensitive high-resolution ion microprobe) Centre, Chinese Academy of Geological Sciences (CAGS), in what could possibly develop into a multi-year commitment to examine the benefits of, and options to achieve, collaborative geoscience activities involving Precambrian geology and geochronology. The Beijing SHRIMP Centre conducts research on Precambrian geology and geochronology to compare and correlate Precambrian marker events from around the world. This work helps geologists gain a better understanding of Precambrian evolution and its mineral deposits. The CAGS is interested in gaining a better understanding of the geology and evolution of the Canadian Shield through collaborative work with the PGS.

The CAGS has established a remote-control SHRIMP work station at the OGS, which allows PGS geoscientists in Sudbury to conduct “hands-on” geochronological determinations on the SHRIMP in China using remote control through the Internet. As part of this pilot project, the Beijing SHRIMP Centre hosted G.M. Stott and J.A. Ayer for 4 weeks in China to conduct collaborative work on geoscience problems that would assist in advancing the understanding of Ontario’s Archean geology. J.A. Ayer also conducted geochronological analysis of several samples from Ontario in collaboration with Chinese geochronologists.

## **Provincial-Scale Metallogenic Compilation and Inventory Studies**

The PGS continued ongoing, multi-year, province-scale projects that fall under the initiative to create inventories of various tectonic settings relevant to mineral exploration, such as 1) the documentation and distribution of FI-, FII- and FIII-type, potentially volcanogenic massive sulphide deposit (VMS)-productive, felsic metavolcanic rocks; 2) determine the characteristics of mineralized intermediate to felsic plutonic systems in the Wabigoon Subprovince (Beakhouse, this volume, Article 13); and 3) update and maintain the geochronology database for Ontario.

## Initiatives Based on Geographic Area

The Abitibi Initiative includes 3 core business projects (*see* Table 2.3) as described above; these projects are in-kind support to the Abitibi project of TGI-3. Other projects in the Abitibi region include

- a 1:100 000 scale compilation of the Ramsey–Algoma region north of Sudbury, which includes the Maple Mountain–Biscotasing area;
- a compilation of nickel-copper-PGE ore compositions from the Abitibi greenstone belt.

The geology and metallogeny of northwest Ontario initiative currently includes 6 core projects:

- a 1:250 000 scale compilation of the Atikokan area resulting from several years of bedrock mapping in the central Wabigoon Subprovince, which is the final stage of completion;
- the western Wabigoon Synthesis, which is a five-year compilation project (Beakhouse, this volume, Article 12);
- completion of the geological map for the Caribou Lake greenstone belt, north of Lake Nipigon;
- completion of the geological map for the Hamlin and Wye lakes area in the Shebandowan greenstone belt;
- 1:20 000 scale bedrock mapping of the Bending Lake greenstone belt (Stone, this volume);
- 1:20 000 scale bedrock mapping of the Lumby Lake greenstone belt (Buse, Lewis and Magnus, this volume);
- completion of 2 legacy projects, which include digitization of a 1:50 000 scale bedrock compilation of the Lake of the Woods region and release of an Open File Report of gold mineralization in the Beardmore–Geraldton area.

The Proterozoic initiative includes 6 core projects:

- 1:20 000 scale bedrock mapping in Cavendish Township in the Central Metasedimentary Belt of the Grenville Province, which is in the final stage of completion;
- a 1:50 000 scale geological compilation of the East Bull Lake and Agnew layered mafic intrusions in collaboration with Laurentian University and Cambrian College, which is also close to completion;
- a continuation of a compilation of the geology of the Midcontinent Rift conducted in collaboration with the United States Geological Survey and the Minnesota Geological Survey;
- ongoing geological, paleomagnetic, geochemical and geochronological studies of Mesoproterozoic Midcontinent Rift–related mafic intrusions near Thunder Bay (Smyk and Hollings, this volume);
- 1:20 000 scale bedrock mapping in the Pecors–Whiskey lakes area at Elliot Lake (Easton, this volume, Article 10);
- a reconnaissance sampling project to assess zinc potential in marbles in the Renfrew region (Easton, this volume, Article 6).

## **Initiatives Involving Geophysical Projects**

Several geophysical projects and activities are described in detail in Rainsford and Muir (this volume). Integration of geophysics into the bedrock mapping projects continues with geoscientists routinely using hand-held magnetic susceptibility meters during mapping as well as a variety of geophysical data and derived products for interpretation.

Modelling of magnetic data has been facilitated by the use of magnetic susceptibility and specific gravity data now routinely collected as part of the bedrock mapping program. Smooth model inversion software and other simpler and faster modelling tools have been acquired to provide insight into specific mapping problems.

## **INTER-JURISDICTIONAL AND COMMITTEE REPRESENTATION**

Staff of the PGS represented the Ontario Geological Survey on several inter-jurisdictional committees, internal committees and associations during the 2009 to 2010 fiscal year, which are summarized in Table 2.1.

## **STAFFING CHANGES IN THE PRECAMBRIAN GEOSCIENCE SECTION**

S. Buse and D. Lewis accepted positions with the PGS as Precambrian Geoscientists in April 2009.

J. Chartrand and J. Webb accepted the positions of Geological Assistant with PGS in April and June, 2009, respectively. P. Gervais accepted the position of Drafter with PGS in August 2009.

L.-A. Bardeggia and K. McCormick were hired as summer assistants to support PGS projects.

T. Brown accepted the position of Manager, Bedrock Mapping & Geophysics in June 2009.

M.G. Houlé left the PGS in June 2009 to accept a position with the Geological Survey of Canada. During his time with PGS, Michel conducted bedrock mapping throughout the Timmins area and produced a series of excellent and detailed bedrock geology maps. His most significant contribution is the work he has done in documenting, characterizing and mapping out the distribution of komatiite metavolcanic flows in the Abitibi greenstone belt. These geoscience data will be used by clients far into the future to explore for komatiite-associated nickel-copper-(PGE) deposits in the Abitibi.

# 3. Project Unit 95-024. A Stratigraphic and Metallogenic Comparison of the Detour–Burntbush Area with the Southern Abitibi Greenstone Belt and Its Implications for Exploration

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## INTRODUCTION

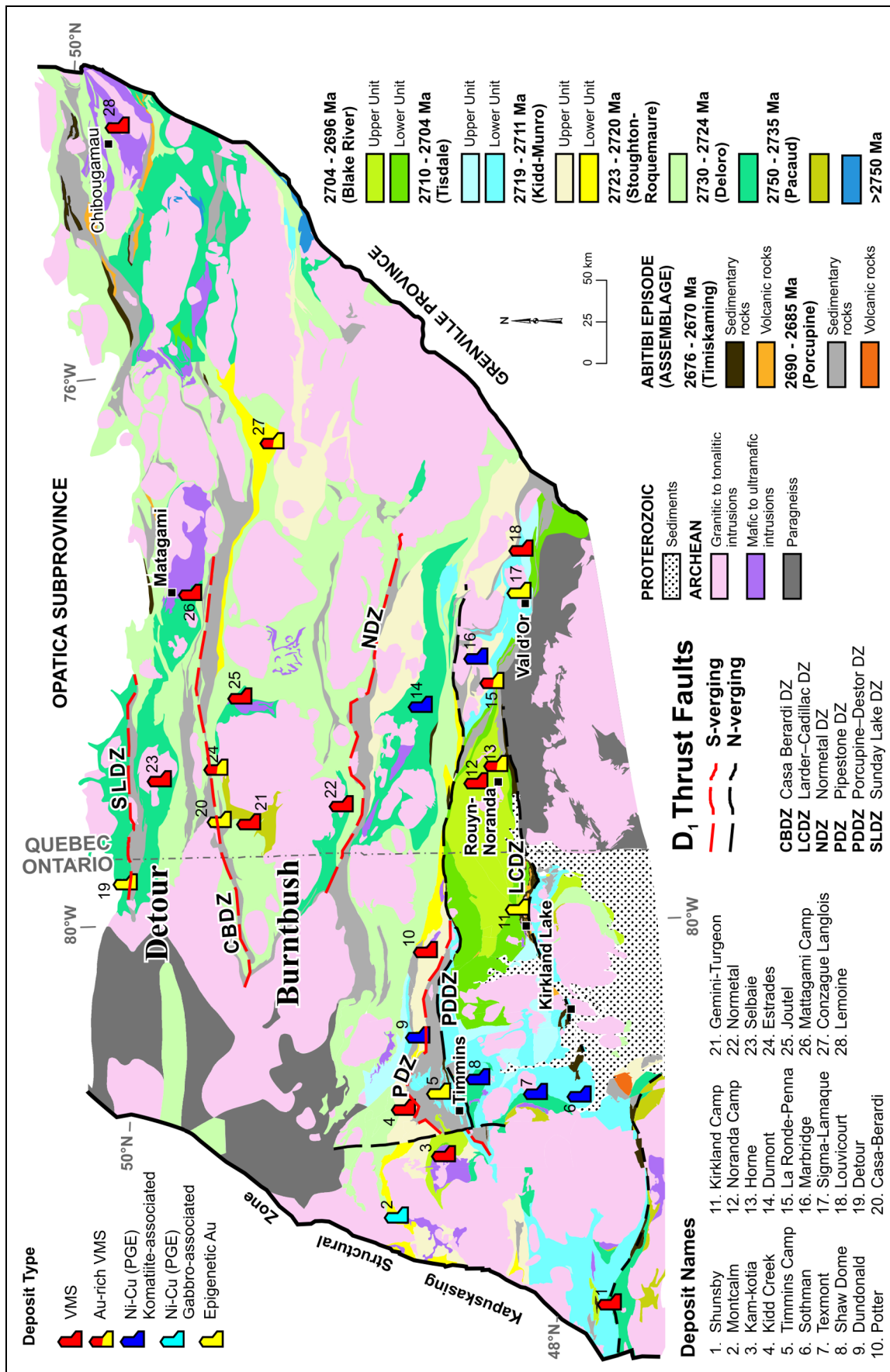
The northwestern portion of the Abitibi greenstone belt (AGB) represents an important and underexplored area for future exploration for base metal and gold deposits, particularly in light of new geoscientific evidence which indicates that the whole AGB evolved as a single autochthonous entity (Ayer et al. 2002; Thurston et al. 2008). In general, this area has extensive overburden cover and, thus, outcrop information is limited. In spite of this drawback, the mineral potential is good with a number of significant past and currently producing deposits (e.g., Selbaie, Normetal, Perseverance–Matagami camp, Detour Lake and Casa-Berardi). It is, therefore, important to compare and contrast the known stratigraphic, metallogenic and structural evolution of the north with the remainder of the AGB to help outline areas of high prospectivity. One such area is the Detour Lake–Burntbush Lake area (Figure 3.1) (referred to here as “Detour–Burntbush area”). Under the Targeted Geoscience Initiative III (TGI-3) Abitibi project (*see* Ayer, Dubé and Calhoun 2008) and the Discover Abitibi Initiative, this part of the AGB has been the focus of a number of new geoscientific projects to improve our understanding of its metallogeny and to aid exploration. The projects include a newly released compilation map, at a scale of 1:100 000, including new geochronology and lithogeochemistry (Ayer et al. 2009a, 2009b); 2 newly released high-resolution aeromagnetic geophysical surveys covering the Detour Lake (OGS 2009a, 2009b) and Burntbush Lake areas (Dumont 2008; Ontario Geological Survey 2009c); ongoing Quaternary mapping and till geochemistry (Gao and Kodors, this volume), and an anticipated project of detailed bedrock mapping, stratigraphy, structure, lithogeochemistry and metallogeny in the southern Burntbush Lake area (*see* [www.discoverabiti.com](http://www.discoverabiti.com)).

## VOLCANOGENIC MASSIVE SULPHIDE-BEARING STRATIGRAPHY

Results from 12 new geochronological samples (Figure 3.2) have greatly improved our understanding of the stratigraphy of the Detour–Burntbush area; these ages now permit better correlation within the AGB stratigraphic framework and with known ages on the Quebec side of the border (Goutier and Melançon 2007). The volcanic rocks in the northwest belong to 3 of the oldest volcanic episodes of AGB, identified as the Pacaud (2750–2735 Ma), Deloro (2734–2724 Ma) and Stoughton–Roquemaure (2723–2720 Ma) assemblages (also identified as volcanic episodes with similar age ranges in Figure 3.1). All 3 assemblages contain VMS deposits and VMS-style mineralization in the northwest AGB.

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*Summary of Field Work and Other Activities 2009,  
Ontario Geological Survey, Open File Report 6240, p.3-1 to 3-7.*



**Figure 3.1.** Stratigraphic map of the Abitibi greenstone belt (modified after Thurston et al. 2008). Abbreviations: DZ, deformation zone; PGE, platinum group elements; VMS, volcanogenic massive sulphide.

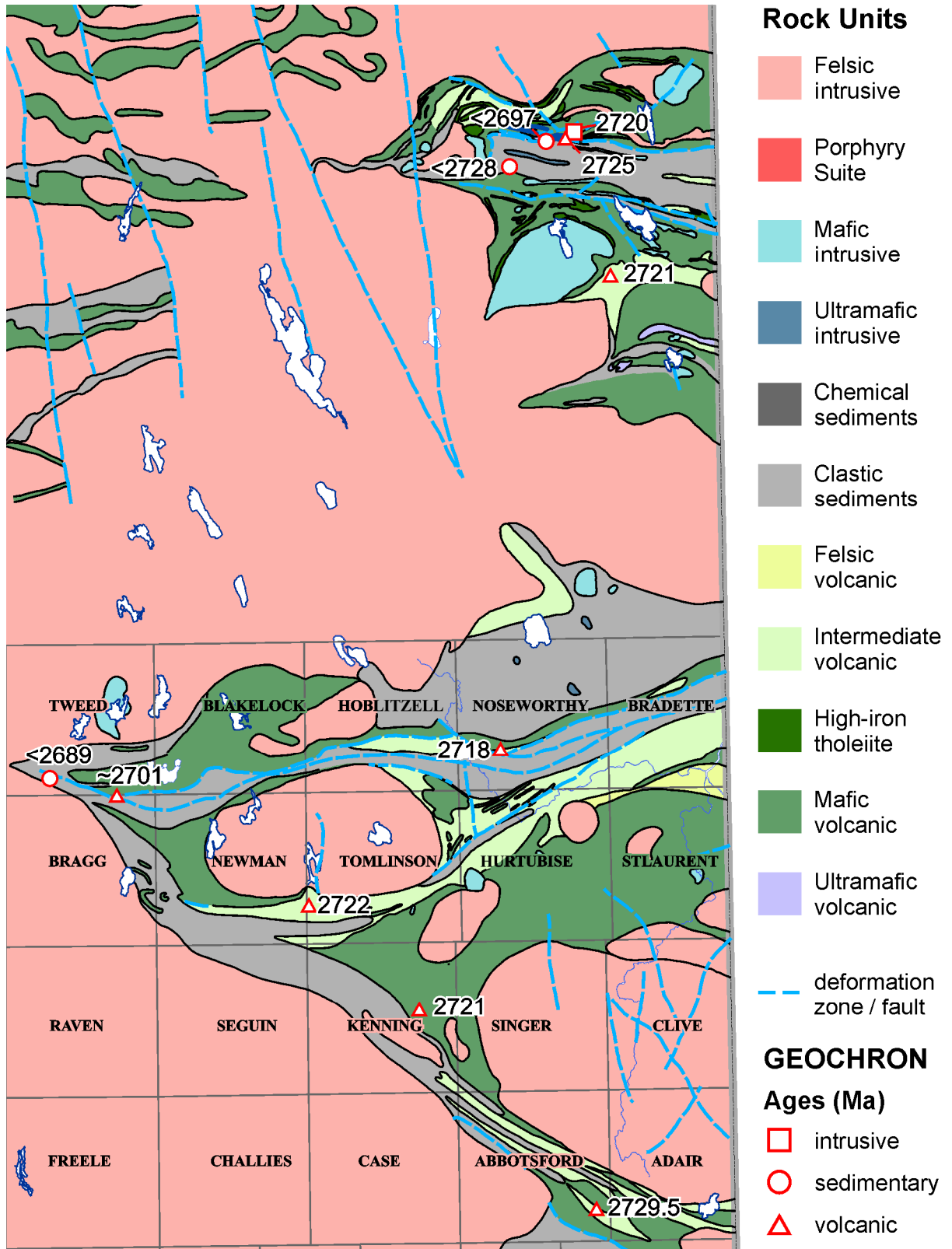


Figure 3.2. Geological map of the Detour-Burntbush area with U/Pb zircon ages (after Ayer et al. 2009a).

The oldest known VMS episode is represented by the ~2 Mt Gemini–Turgeon deposit hosted within a thin unit of felsic volcanic rocks with an age of  $2736 \pm 1$  Ma (Goutier and Melançon 2007). This deposit is located about 15 km east of the interprovincial border in a thin calc-alkalic felsic unit capping a thick succession of mafic volcanic rocks on the northwest side of the Mistaouac pluton. It is as yet uncertain if the stratigraphy containing the deposit continues into northeast Ontario as no volcanic rocks of this age have been found as yet in either the Burntbush or Detour areas.

The Deloro assemblage is a very prolific metallogenic episode in the AGB containing 27 VMS deposits totalling about 111 Mt. In northwest Quebec, VMS deposits similar in age to the Deloro assemblage include the Selbaie, Joutel and Normetal deposits (Thurston et al. 2008). New geochronological results from the Detour area indicate an intermediate calc-alkalic marker horizon has an age of  $2725 \pm 1$  Ma. This marker horizon lies at the contact between a lower ultramafic volcanic unit and an upper mafic volcanic unit all of which are hosts to the Detour gold mineralization. This age indicates that the volcanic sequence belongs to the Deloro assemblage. The predominantly mafic volcanic rocks in this area have striped magnetic patterns caused by alternating high and low iron tholeiitic units. Although no geochronology has been done on the volcanic units south of an extensive band of Porcupine assemblage clastic sedimentary rocks ( $<2697$  Ma), they have similar magnetic patterns to the volcanic units to the north. This geophysical pattern is traceable for at least 40 km to the southeast where felsic volcanic rocks hosting the ~30 Mt Selbaie deposit have an age of  $2729 \pm 3$  Ma (Goutier and Melançon 2007), confirming a Deloro assemblage correlation from Selbaie to both south and north of the east-trending band of Porcupine assemblage sediments. This suggests felsic volcanic units occurring within this part of the Deloro assemblage should be a focus of exploration for Selbaie-type zinc-copper-silver-gold VMS deposits.

About 100 km to the south, felsic volcanic rocks hosting the ~10 Mt Normetal VMS deposit have an age of  $2728 \pm 2$  Ma (Goutier and Melançon 2007). This deposit lies about 10 km east of the interprovincial border; however, new geochronology and geochemistry results indicate that this productive volcanic stratigraphy extends westward into the southern Burntbush area where an age of  $2729 \pm 2$  Ma has been determined in felsic volcanic rocks in Abbotsford Township (see Figure 3.2). This part of the Burntbush area has numerous iron formation units and electromagnetic conductors as well as felsic volcanic rocks with transitional chemical affinity, features similar to the host rocks of the Normetal deposit. Within this geological setting, any evidence of carbonate, sericite and/or chloritoid hydrothermal alteration with anomalous base metal values should be considered highly prospective targets for VMS-style mineralization (Lafrance et al. 2000).

The central and northern Burntbush areas, and the southern Detour area are underlain by extensive volcanic units of the Stoughton–Roquemaure assemblage (2723–2720 Ma), locally with structurally interleaved units of Porcupine assemblage clastic sedimentary rocks (2690–2685 Ma) (see Figures 3.1 and 3.2). The Stoughton–Roquemaure assemblage is host to the ~1 Mt gold-rich Estrades VMS deposit, about 40 km east of the Ontario–Quebec provincial border, which is found within tholeiitic mafic to felsic volcanic rocks with an age of  $2720 \pm 3$  Ma (Goutier and Melançon 2007). The volcanic rocks hosting the deposit lie immediately south of an extensive band of Porcupine assemblage sediments extending westward across the northern Burntbush area. A recent copper- and zinc-rich VMS discovery, in similar age stratigraphy and located 3.7 km east of the Estrades Mine, reported impressive mineralized intercepts including 3.8% Cu, 6.0% Zn, 1.7 g/t Au and 52.2 g/t Ag over 2.3 m (Cogitore Resources Inc., news release, April 27, 2009, see [www.cogitore.com/press\\_releases/2009-apr27.htm](http://www.cogitore.com/press_releases/2009-apr27.htm)). This discovery illustrates the high potential of the area and this stratigraphic unit in particular. The presence of zinc- and gold-rich volcanogenic mineral occurrences in locations such as Noseworthy Township and the Atkinson Lake area associated with volcanic rocks with newly determined ages of  $2718 \pm 3$  Ma and  $2721 \pm 2$  Ma, respectively, (see Figure 3.2) indicates the potential for other gold-rich VMS deposits within this assemblage which is widespread throughout the northwestern AGB (see Figure 3.1). Quartz-sericite schists with manganese-

rich garnet and/or aluminous minerals and anomalous gold and base metal values in intermediate to felsic transitional to calc-alkalic volcanic or volcanoclastic rocks located underneath a sedimentary cover are considered to be among the most prospective targets for gold-rich VMS in metamorphosed terranes (e.g., Dubé et al. 2007).

## EPIGENETIC GOLD

As is true for the whole of the Abitibi greenstone belt, structurally controlled gold deposits in the northwest AGB are genetically and spatially associated with major deformation zones. These fault zones were the locus of repeated strain increments resulting in broad easterly trending, ductile deformation zones with kinematics commonly indicating a long-lived and complex deformation history. Typically, the “breaks” occur at contacts between volcanic and younger sedimentary assemblages (including both the Porcupine (2690–2685 Ma) and the Timiskaming (2676–2670 Ma) assemblages). Where kinematic studies have been done, they typically show early dip-slip displacement associated with north-south compression followed by sinistral and/or dextral displacement associated with various transpressive events (e.g., Bateman, Ayer and Dubé 2008; Ispolatov et al. 2008 and references therein). Recent studies have also shown the gold was emplaced episodically from about 2680 to 2665 Ma and is commonly concentrated in higher order hanging-wall faults in close proximity to the major breaks.

Recent geochronological and structural studies at the Detour Lake Mine (J. Oliver, J. Ayer, B. Dubé, R. Aubertin, M. Bursen, G. Pennaton and R. Friedman, unpublished data from joint collaboration, 2009) show that the Sunday Lake deformation zone (SLDZ) represents a north-dipping  $D_1$  fault in which volcanic rocks, similar in age to the Deloro assemblage, were thrust southerly over clastic sedimentary rocks of the Porcupine assemblage. Subsequent strike-slip deformation events overprint the  $D_1$  event with both dextral and sinistral asymmetry. Gold mineralization occurs in the hanging wall to the Sunday Lake deformation zone in both narrow high-grade zones at the contact between ultramafic and mafic volcanic units and also as broad bulk tonnage lower grade zones in the mafic flows. Geochronology indicates that barren albitite dikes cutting the gold zones are a late magmatic event containing inherited zircons indicating emplacement after *circa* 2697 Ma. This indicates that epigenetic gold mineralization at Detour Lake is not synvolcanic as was previously interpreted by Marmont and Corfu (1989). Similar albitite dikes in the southern AGB have magmatic ages ranging from 2776 to 2672 Ma and in the Timmins camp are synchronous with early gold mineralization, but are cut by the main stage auriferous quartz-carbonate veins (Bateman et al. 2008). Thus, Detour Lake gold mineralization is potentially older than the main gold event in the southern AGB. This style of gold mineralization along the Sunday Lake deformation zone may have been underexplored on both sides of the Quebec–Ontario provincial border.

The Casa Berardi deformation zone hosts the Casa-Berardi gold mine and extends westward across the northern Burntbrush area (*see* Figures 3.1 and 3.2). Structural studies at the Casa-Berardi Mine by Pilote et al. (1990) indicate the deformation zone consists of broad anastomosing shears with early north-side-up, dip-slip displacement and with gold occurring in quartz veins in later faults with somewhat shallower dips. Detrital zircon geochronology from clastic sedimentary units in the vicinity of the mine indicates a deposition age of <2696 Ma (Goutier and Melançon 2007). This, in conjunction with an age of deposition of <2689 Ma from a sandstone unit at the western extent of the sedimentary belt in Tweed Township (*see* Figure 3.2), indicates the sedimentary unit is part of the Porcupine assemblage. Thus, the structural setting of the Casa Berardi deformation zone (CBDZ) shares analogies with the Sunday Lake deformation zone with older volcanic units thrust southerly over a sedimentary unit equivalent in age to the Porcupine assemblage. Explorationists should, therefore, focus their efforts on this extensive Casa Berardi deformation zone and its western extension in Ontario as there are numerous epigenetic gold occurrences documented within the Porcupine assemblage sediments and in the hanging-wall volcanic rocks immediately to the north. Changes in the directions of the faulted contact between the Porcupine

sediments and the hanging-wall volcanic rocks could constitute dilational sites favourable for gold-bearing fluid circulation and gold deposition.

Large-scale south-verging thrusts can be found as far south as Timmins where the Pipestone deformation zone (PDZ) marks the southern contact between Kidd–Munro assemblage volcanic rocks (2719–2711 Ma) and the Porcupine assemblage (Berger, Rainsford and Carter-McAuslan 2008; Bleeker, van Breemen and Berger 2008). Similar to the northern thrusts, epigenetic gold is commonly found in the hanging wall of the PDZ thrust. Recent geochronology results show that the PDZ extends west of Timmins. Here, the new Lake Shore Timmins gold mine in Bristol Township lies at a thrust contact between the Kidd–Munro and Porcupine assemblages where it has been intruded by a late syenitic to ultramafic intrusive complex. Thus, the PDZ represents an important and yet underexplored target for gold exploration within the prolific Timmins gold camp region.

Immediately south of the PDZ, large-scale breaks such as the Porcupine–Destor deformation zone (PDDZ) and Larder–Cadillac deformation zone (LCDZ) differ from the northern faults discussed above in that they have younger associated sedimentary units of the Timiskaming assemblage (2676–2670 Ma). The Porcupine–Destor deformation zone also truncates the PDZ (*see* Figure 3.1) (Bleeker, van Breemen and Berger 2008) and, within the Ontario portions of these southern deformation zones, they have opposing north-verging displacement vectors (Bateman, Ayer and Dubé 2008; Ispolatov *et al.* 2008 and references therein). Collectively, the above features may indicate that an additional and potentially earlier epigenetic gold episode could account for the greater endowment of mining camps, such as Timmins and Kirkland Lake, which are proximal to the north-verging thrusts in the southern AGB.

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# 4. Project Unit 06-001. Preliminary Ideas on the Stratigraphy, Geochemistry and Geochronology of the Kidd–Munro Assemblage

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## INTRODUCTION

Multi-disciplinary studies carried out over the last 3 years under the Targeted Geoscience Initiative III (TGI-3) Abitibi project in the Kidd–Munro assemblage are nearing completion and synthesis of results is underway. Geologic mapping and compilation (Berger and McIlraith 2007; Berger 2008; Berger, Houlié and Dinel 2009; É. Dinel, unpublished data) as well as thematic studies by Dinel et al. (2008), Chapman, Peters and Layton-Matthews (2008), Préfontaine et al. (2008) and Berger, Rainsford and Carter-McAuslan (2008) have provided new insight into the Kidd–Munro assemblage. Jackson and Fyon (1991) first defined the Kidd–Munro assemblage based on rock type and chemical affinity. Ayer et al. (2002) revised and expanded the assemblage to include time equivalent rock suites (i.e., 2719 to 2710 Ma) and subdivided it into tholeiitic and calc-alkalic units. The TGI-3 program has resulted in further revision to the extent and nature of the Kidd–Munro assemblage. This article will examine aspects of the geologic mapping as it pertains to the stratigraphy, geochemistry and geochronology for part of the Kidd–Munro assemblage.

## EXTENT OF THE KIDD–MUNRO ASSEMBLAGE

Figure 4.1 shows the extent of the Kidd–Munro assemblage and its subdivision into the 2 main lithochemical subdivisions based on recent mapping, geochemistry and new geochronology. The assemblage has now been expanded to include tholeiitic and calc-alkalic metavolcanic rocks, with ages within the established range of the Kidd–Munro assemblage, in an arm extending to the west in northern Coulson, Wilkie and Dundonald townships. These rocks are known mostly from diamond-drill core and a few scattered outcrops, but their field relationships demonstrate that the calc-alkalic and tholeiitic rocks are intercalated. Contacts with other assemblages are inferred to be largely fault bounded and the interpreted pattern on an area map suggests imbricate panels of different assemblages make up the geology. The calc-alkalic unit is largely confined to the north and east parts of the assemblage, but also occurs as narrow, discontinuous wedges of rock within the tholeiitic unit. The tholeiitic unit is more extensive and more complicated than the calc-alkalic unit. Rocks with both tholeiitic and transitional geochemistry are mixed throughout the unit and recent work by Dinel et al. (2008) demonstrated that, locally, the 2 rock types could be divided into stratigraphic formations. Work is ongoing to subdivide the rest of the tholeiitic unit into formations.

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*Summary of Field Work and Other Activities 2009,  
Ontario Geological Survey, Open File Report 6240, p.4-1 to 4-8.*

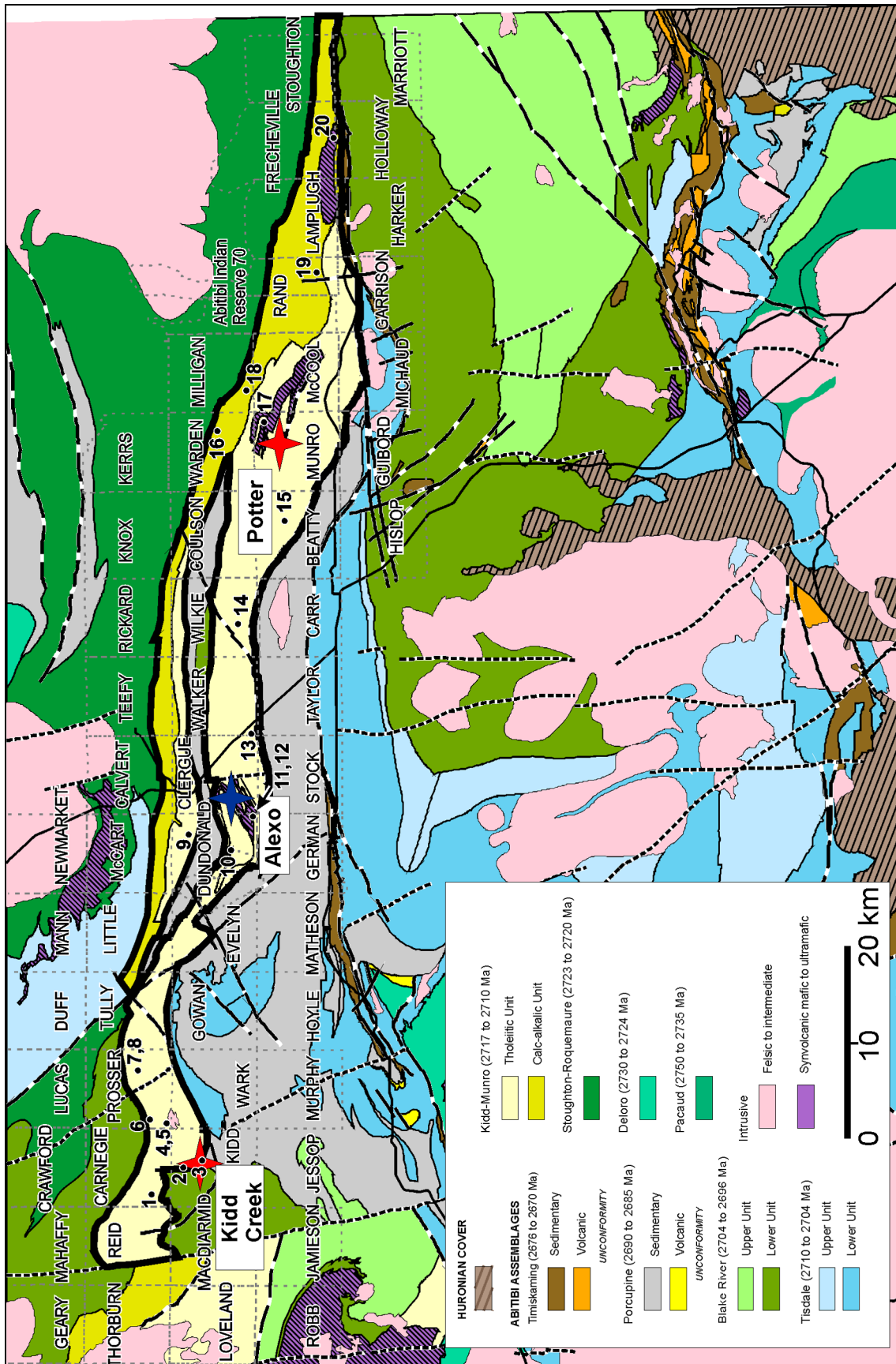


Figure 4.1. Location (indicated by thick black outline) of the Kidd-Munro assemblage in Ontario.

## Calc-Alkalic Unit

The calc-alkalic unit of the Kidd–Munro assemblage extends approximately 100 km from Little Township to just west of the Quebec border (*see* Figure 4.1). The unit is poorly exposed and is known mostly from diamond-drill core and scattered outcrops in Rand, Lamplugh and Frecheville townships (*see* Figure 4.1). The unit is fault bounded with the Stoughton–Roquemaure assemblage to the north and is intercalated with tholeiitic rocks of the Kidd–Munro assemblage to the south. The contact with the Tisdale assemblage is inferred from airborne geophysical data in Tully and Little townships.

The calc-alkalic rocks are characterized by plagioclase and less commonly pyroxene and/or amphibole porphyritic pyroclastic and epiclastic deposits with subordinate massive and pillowed flows. A possible volcanic centre, recognized by coarse pyroclastic deposits and feldspar porphyritic flows, dikes and small intrusions, is located in Rand Township (Jensen 1982; Berger, Luinstra and Ropchan 2002). The fragmental rocks tend to become finer grained, better sorted and more heterolithic east and west of this area suggesting that they were deposited distal to, and on the flanks of a volcanic edifice centred in Rand Township. Volcanogenic massive sulphide (VMS)-style zinc mineralization in northern Coulson Township may be related to distal fumarolic activity related to the creation of the volcanic edifice. The contact with the tholeiitic unit is abrupt to the south where the calc-alkalic unit is thickest (Coulson, Warden and Rand townships), but becomes intercalated with tholeiitic metavolcanic rocks both to the east and west.

The calc-alkalic rocks are predominantly andesite and dacite in composition with lesser basalt and rhyolite. Geochemically, these rocks are characterized by  $Zr/Y \geq 7$ , steep negatively sloped chondrite-normalized rare earth element (REE) patterns and pronounced primitive mantle depletions in niobium, tantalum and titanium with elevated thorium. Similar geochemical patterns are interpreted as island arc signatures related to active plate subduction and are observed in many rock suites throughout the Abitibi (Ayer et al. 2002; Henderson 1984).

Five high-precision U/Pb zircon geochronology samples bracket the age of the calc-alkalic rocks between 2716 and 2713 Ma and these ages overlap with those from the tholeiitic unit (*see* below). This indicates synchronous development of the 2 units and, thus, it is no surprise that calc-alkalic and tholeiitic rocks are intercalated at various locations throughout the Kidd–Munro assemblage.

## Tholeiitic Unit

The tholeiitic unit of the Kidd–Munro assemblage extends approximately 130 km from west of the Kidd Creek Mine to the vicinity of the Holloway gold mine (*see* Figure 4.1) where it is structurally interleaved with Timiskaming metasedimentary rocks (2676 to 2670 Ma) in the Porcupine–Destor fault zone. The unit varies from 1.5 up to 12 km wide (Munro Township) and is volumetrically the largest unit in the Kidd–Munro assemblage. The unit is fairly well defined from the mapping and airborne geophysical coverage; however, the western limit is poorly constrained due to lack of outcrop and lack of suitable material for age determinations. Additionally, the extent of tholeiitic metavolcanic rocks now known to be part of the Kidd–Munro assemblage in north Dundonald and Clergue townships is poorly constrained.

The tholeiitic unit is composed of mafic, intermediate and felsic metavolcanic rocks, related subvolcanic intrusions and komatiitic rocks. Massive and pillowed mafic flows are dominant and numerous gabbroic textured sills, dikes and small intrusions are common throughout the unit. Pillow breccia, flow breccia and hyaloclastite are locally abundant. Heterolithic breccias are common only in Kidd and Prosser townships and probably represent deposits along synvolcanic faults near the edges of rifted basins. These deposits are generally capped with fine-grained tuff, chert, graphite and interflow metasedimentary rocks that likely represent localized hiatus in volcanism.

Intermediate metavolcanic rocks are interspersed throughout the mafic metavolcanic rocks and are most abundant in Prosser and Dundonald townships where locally thick accumulations occur. “Intermediate” is herein used as field terminology to separate pale green pillow breccia, pillowed flows tuff and tuff breccia from dark green to black mafic metavolcanic rocks. Geochemistry is not implied as intermediate rocks display tholeiitic, calc-alkalic and transitional geochemical affinities (see below). Feldspar phenocrysts occur locally, but most rocks are aphyric. Pillows are irregular to well formed and commonly grade across and along strike into pillow breccia. Amygdules are common, varioles are rare.

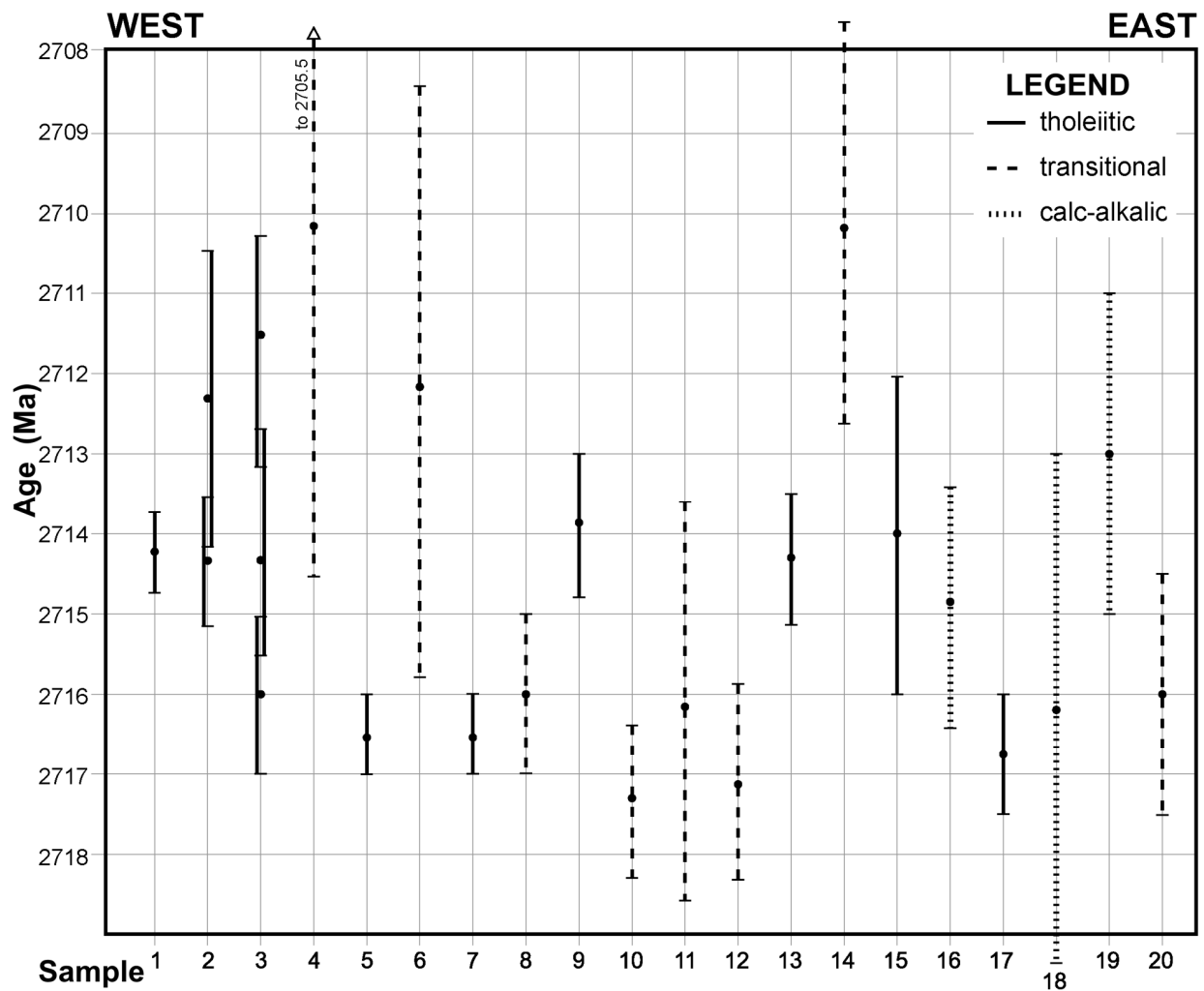
Felsic metavolcanic rocks composed of massive and laminated flows, autoclastic flow breccias, subvolcanic sills and domes and less commonly pyroclastic tuff and tuff breccia are irregularly distributed in the tholeiitic unit. The thicker accumulations of felsic rocks occur at the Kidd Creek deposit and in Carnegie, Prosser, Wilkie and Beatty townships. Less extensive felsic rock units occur in Dundonald, Clergue and Munro townships. Several studies at the Kidd Creek deposit indicate the base metal mineralization is hosted in subaqueous high silica rhyolite extruded into a graben or half-graben analogous to modern-day Iceland (Bleeker 1999; Prior et al. 1999). Moulton (2009) concluded that felsic rocks in Prosser Township are stratigraphically and chemically equivalent to the Kidd Creek deposit and formed as narrow, subaqueous flows possibly on the flanks of a volcanic vent. Felsic metavolcanic rocks in Wilkie Township are a mixture of flows, pyroclastic and epiclastic rocks with mixed geochemical affinity and appear to occur as 2 horizons separated by a narrow band of ultramafic and mafic metavolcanic flows. Massive and autobrecciated rhyolite in Beatty and Munro townships occur as flows and subvolcanic sills; whereas, spherulitic rhyolite at the south contact of the Kidd–Munro and Porcupine assemblages is dominantly composed of massive flows and lobes. Felsic rocks in Dundonald Township are mostly tuff breccia possibly related to a hydrothermally altered subvolcanic intrusion encountered in nearby diamond drilling. Overall, the main effusive centres occur in Kidd and Prosser Townships, whereas the other felsic metavolcanic rocks appear to be related to fissure eruptions or are subvolcanic sills.

The tholeiitic unit is divisible into 2 geochemical suites. Tholeiitic rocks are characterized by  $Zr/Y \leq 4$ , flat chondrite-normalized REE patterns and depleted primitive mantle thorium. This suite is strongly bimodal between basalt and rhyolite flows with subordinate fragmental units and numerous subvolcanic (gabbroic) units. Iron and magnesium basalts are most common and include the mid-oceanic ridge basalt (MORB)-like flows and primitive arc tholeiites described by Wyman, Bleeker and Kerrich (1999) at Kidd Creek deposit. A transitional suite of rocks is characterized by  $Zr/Y$  between 3 and 7, negatively sloped light REE (LREE) and flat heavy REE (HREE) chondrite-normalized patterns, with weakly depleted niobium, tantalum and elevated thorium compared to primitive mantle. This suite is composed of basalt, andesite, dacite and rare rhyolite that are typically fragmental, locally very amygdaloidal, and may contain anhedral to euhedral plagioclase phenocrysts from 1 to 10 mm in size. These rocks are closely associated with the tholeiitic suite, but their distribution is poorly constrained. Compositionally, they correspond to the evolved arc tholeiites, icelandites and some of the felsic rocks at Kidd Creek deposit (Wyman, Bleeker and Kerrich 1999). Recent mapping indicates that the transitional suite underlies the tholeiitic suite and may aid in stratigraphic subdivision into formations throughout the assemblage (Berger and McIlraith 2007; Diné et al. 2008).

Numerous high-precision U/Pb zircon ages from the felsic and intermediate metavolcanic rocks indicate that the tholeiitic unit varies between 2717 and 2710 Ma. Figure 4.2 shows that, although there is overlap in the error bars, ages cluster at slightly older than 2716 Ma, slightly older than 2714 Ma and at approximately 2710 Ma. The oldest ages correspond with transitional intermediate and felsic metavolcanic rocks that are coeval with komatiites that host the Alexo and Kelex nickel deposits in Dundonald Township. Tholeiitic and transitional felsic metavolcanic rocks with an age of approximately 2716 Ma occur at the Kidd Creek deposit and in Prosser and Munro townships. Calc-alkalic volcanism was initiated at 2716 Ma in the eastern part of the Kidd–Munro assemblage. The main pulse of calc-alkalic volcanism and a second pulse of largely tholeiitic volcanism occurred at 2714 Ma throughout the assemblage (see Figure 4.2).

Late, probably resurgent, tholeiitic and transitional volcanism occurred in isolated areas at approximately 2710 Ma and marked the end of volcanism in the Kidd–Munro assemblage.

Komatiitic rocks comprise approximately 10% of the Kidd–Munro assemblage (Barrie 1999a) and are distributed from the Kidd Creek Mine to the Holloway Mine. Houlé et al. (2008) indicated that komatiites occur in at least 3 stratigraphic intervals within the tholeiitic unit of the Kidd–Munro assemblage. The oldest komatiitic rocks are the most voluminous and most widespread in the Kidd–Munro assemblage. This komatiitic horizon occurs in the footwall at the Kidd Creek deposit where they are coeval with felsic metavolcanic rocks with an age of 2716 Ma (Bleeker, Parrish and Sager-Kinsman 1999). It appears that komatiites at the Kidd Creek deposit are stratigraphically equivalent to the komatiites in Dundonald Township where the komatiites hosting magmatic nickel-copper mineralization overlie and display peperitic textures with felsic rocks with an age of 2717 Ma (Houlé et al. 2008; see Figure 4.2). Barrie et al. (1999) indicate that a narrow komatiite unit underlies the 2717 Ma felsic rocks in Dundonald Township suggesting a slightly older komatiitic unit also occurs in this area. Komatiite units in north Munro Township include Pyke Hill, Fred’s and Theo’s flows, the Potter copper-zinc mine and the Potterdoal copper-zinc mine stratigraphy. Southward-facing felsic metavolcanic screens within the



**Figure 4.2.** Distribution of age dates with error bars for the Kidd–Munro assemblage. Geochronology data sources: sample numbers 1–5 from Bleeker (1999); numbers 6, 8–10 from Berger (this study); numbers 7, 11, 17 from W. Bleeker (GSC, personal communication, 2006 and 2008); numbers 12, 14, 18 from Barrie (1999b); numbers 13, 16, 20 from Ayer et al. (2002); and numbers 15, 19 from Corfu et al. (1989).

Warden Hill gabbroic intrusion (2705 Ma) have an age of  $2716.8 \pm 0.8$  Ma. They occur in the footwall to the Potterdoal Mine and in komatiites in northern Munro Township. This would make this stratigraphy equivalent to that hosting the Kidd Creek and Dundonald Township komatiites and, furthermore, indicates that the copper-zinc VMS-style mineralization in Munro Township is coeval with that at the Kidd Creek deposit.

Komatiitic rocks that host the Mickle nickel showing in the south parts of Munro and Beatty townships are over 1250 m thick and overlie felsic extrusive rocks with an age of 2714 Ma (Corfu et al. 1989; *see* Figure 4.2). These komatiites are distinctly younger than those at Kidd, Dundonald and northern Munro townships and, thus, comprise the second komatiitic stratigraphic unit. Komatiites associated with this stratigraphic unit occur mainly in south Munro Township and are volumetrically less than those produced at 2716 Ma.

Thin discontinuous komatiite flows occur along the axis of a major syncline that extends from Munro Township west to Wilkie Township. In Wilkie Township, komatiitic rocks lie stratigraphically above, and are interlayered with, felsic metavolcanic rocks with an age of  $2710 \pm 2.5$  Ma (*see* Figures 4.1 and 4.2). These komatiite flows comprise the third stratigraphic unit and are the youngest ultramafic rocks in the Kidd–Munro assemblage.

Barrie (1999b) and Wyman, Bleeker and Kerrich (1999) indicate that the komatiites at Kidd Creek are not depleted in aluminum and are geochemically similar to komatiites in the Pyke Hill area of Munro Township. Geochemistry of the other komatiite horizons has not been studied and work is ongoing to determine if the geochemistry of the komatiites varies with stratigraphy.

## SUMMARY

The Kidd–Munro assemblage is expanded to include intercalated tholeiitic and calc-alkalic metavolcanic rocks in north Dundonald Township. These rocks extend east and include a thick succession of calc-alkalic pyroclastic and epiclastic rocks in Coulson and Warden townships. The western extent of these rocks is under investigation, but possibly includes intermediate fragmental rocks in Little and Tully townships.

The original subdivision of the Kidd–Munro assemblage into tholeiitic and calc-alkalic units of Ayer et al. (2002) is confirmed with additional geochemistry and geochronology. The calc-alkalic unit underlies much of the northeast part of the assemblage and is composed mostly of andesitic and dacitic pyroclastic and epiclastic rocks. Calc-alkalic volcanism commenced at 2716 Ma and was mostly complete by 2713 Ma. A preliminary interpretation by the authors infers that the unit is restricted in time and space and was produced by a volcanic edifice in the eastern part of the assemblage.

The tholeiitic unit is complex with several rock types and geochemical suites. Intermediate and felsic metavolcanic rocks with transitional geochemistry have an age of 2717 Ma in Dundonald Township and appear to be the oldest rocks in the Kidd–Munro assemblage. Dinel et al. (2008) also demonstrated that rocks with transitional geochemistry underlie rocks with tholeiitic geochemistry in Walker and Clergue townships. The most voluminous part of the tholeiitic unit is composed of mafic and felsic tholeiitic metavolcanic rocks that occur from the Kidd Creek deposit to Holloway Township. Volcanism appears to be episodic with the first pulse commencing at 2716 Ma, shortly after or synchronous with the transitional rocks in Dundonald Township. A second tholeiitic pulse occurred *circa* 2714 Ma and appears to be equally widespread as the first pulse but less voluminous. The youngest volcanic event *circa* 2710 Ma is spatially restricted and geochemically diverse producing felsic metavolcanic rocks of tholeiitic and transitional affinities. Komatiitic rocks occur at 3 stratigraphic intervals in the tholeiitic unit and each is closely linked in time to the pulses of tholeiitic volcanism.

A preliminary reconstruction of the tholeiitic unit would entail eruption of a volcanic substrate with transitional geochemistry that is widespread throughout the Kidd–Munro assemblage. The transitional rocks are rifted with intrusion and extrusion of abundant mantle plume–derived komatiites similar to the scenario described by Houlé et al. (2008b). At about the same time, rifting at the Kidd Creek area and in the vicinity of Pyke’s Hill in Munro Township also produced large volumes of komatiite. Tholeiitic felsic volcanism accompanied the komatiites at the Kidd Creek area and is host to the giant Kidd Creek base metal deposit. There is very little felsic volcanism preserved in the Pyke’s Hill area; instead base metal mineralization is hosted in komatiitic and mafic tholeiitic rocks at the Potter Mine. A second pulse of felsic tholeiitic volcanism was triggered at 2714 Ma with main eruptive centres at the Kidd Creek area and in the Beatty Township area. The felsic metavolcanic rocks cap the base metal mineralization at the Kidd Creek deposit, host the zinc mineralization at the Chance prospect, but as yet are not known to host base metal mineralization in the Beatty Township area. Thick accumulations of komatiite overlie felsic metavolcanic rocks of age 2714 Ma in Beatty and south Munro townships and are interpreted as the products of a second surge of magma from the same mantle plume that formed the lower komatiite horizon. Nickel mineralization is associated with these komatiites. Tholeiitic volcanism continues intermittently as indicated by several narrow rhyolite horizons with ages between 2714 and 2710 Ma at various locations in the tholeiitic unit. In Wilkie Township, felsic tuff mixed with argillite and interlayered with komatiite flows has an age of 2710 Ma and represents the final stage of volcanism in the Kidd–Munro assemblage. These felsic rocks display mixed transitional and tholeiitic geochemistry and likely represent a late resurgent pulse of magmatism possibly related to the waning influence of the mantle plume that produced the associated and underlying komatiites. Hydrothermal activity affected the felsic and underlying mafic metavolcanic rocks as indicated by widespread chlorite and sericite alteration in this area.

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# 5. Project Unit 06-002. Geology, Mineral Potential and Preliminary Geological Interpretation of the Bartlett and Halliday Domes, Abitibi Greenstone Belt, in Semple and Hutt Townships, Ontario

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## INTRODUCTION

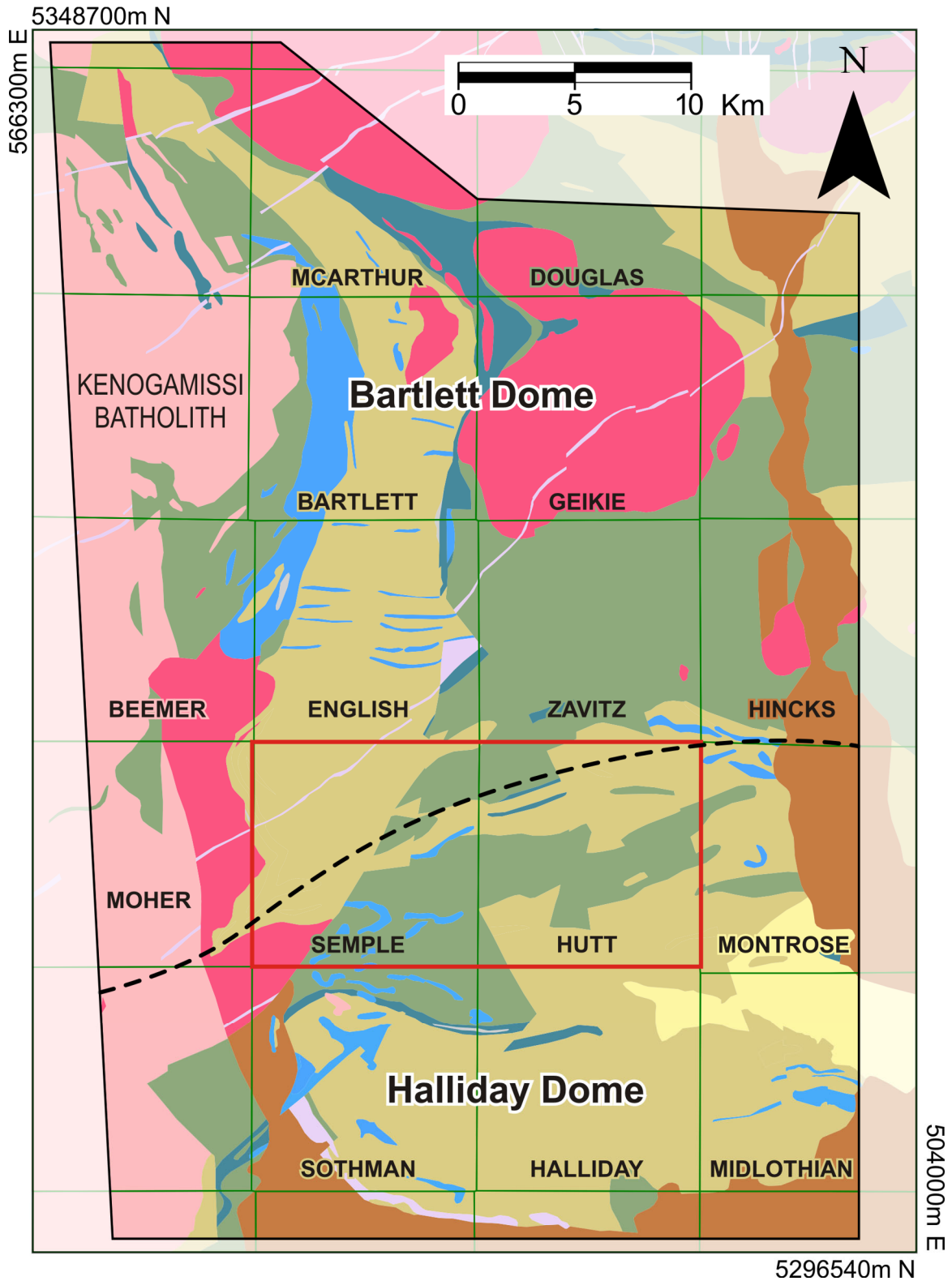
The mapping carried out in Semple and Hutt townships is part of a multi-year bedrock mapping project that began in 2006 to update the geological knowledge of the southern part of the Timmins mining camp. During the summer of 2009, mapping focussed mainly on Semple and Hutt townships, at a scale of 1:20 000 (Figure 5.1). However, some geological verification was also conducted in parts of English, Zavitz, Montrose and Bannockburn townships, and geological reconnaissance was conducted in the eastern part of Beemer and Moher townships as well as the western part of Hincks Township. The goals of this multi-year project are to 1) update the geological mapping in the Bartlett and Halliday domes, last mapped in the 1970s and 1950s (Pyke 1978; Bright 1984); 2) clarify and characterize the major lithological units; 3) better understand the stratigraphy; and 4) evaluate the mineral potential of the area. The Bartlett and Halliday domes mapping project is part of the core program of the Precambrian Geoscience Section (PGS) and represents an in-kind contribution to the Targeted Geoscience Initiative III (TGI-3) Abitibi project, a multidisciplinary collaboration with the Geological Survey of Canada (GSC) and Géologie Québec.

## GENERAL GEOLOGY

The Abitibi greenstone belt consists of a stratigraphically continuous succession of Archean metavolcanic and metasedimentary rocks that developed in an ensimatic basin (Ayer et al. 2002). These rocks have been subdivided into 8 temporally constrained lithotectonic assemblages by Ayer et al. (1999a, 1999b, 2002, 2005) and Ayer, Ketchum and Trowell (2002). Six of these assemblages are dominantly volcanic: Pacaud, Deloro, Stoughton–Roquemaure, Kidd–Munro, Tisdale and Blake River, and 2 are dominantly sedimentary: Porcupine and Timiskaming. More recently, Thurston et al. (2008) have proposed some revision to the Abitibi-wide stratigraphy and reaffirmed the implied autochthonous development of the volcanic stratigraphy. They propose subdividing the Abitibi greenstone belt into 7 discrete volcanic episodes: pre-2750 Ma; 2750–2736 Ma (Pacaud assemblage); 2734–2724 Ma (Deloro assemblage); 2723–2720 Ma (Stoughton–Roquemaure assemblage); 2719–2711 Ma (Kidd–Munro assemblage); 2710–2704 Ma (Tisdale assemblage); and 2704–2695 Ma (Blake River assemblage), followed by 2 successor basins, referred to as the Porcupine-type (2690–2685 Ma) and Timiskaming-type (2676–2670 Ma) basins. Significant depositional gaps marked by chemical sediments are found between and within many of the assemblages.

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*Summary of Field Work and Other Activities 2009,  
Ontario Geological Survey, Open File Report 6240, p.5-1 to 5-17.*



**Figure 5.1.** General location map of the east part of the Kenogamissi batholith. The red outline indicates 2009 bedrock mapping area in Hutt and Semple townships. The black dashed line marks the approximated boundary between the Bartlett Dome to the north and the Halliday Dome to the south.

The majority of the Bartlett Dome was mapped in previous years (Houlé 2006, 2007; Houlé and Solgadi 2007; Houlé, Baldwin and Thurston 2008; Houlé, Solgadi and Préfontaine 2009); however, the southern part of the Bartlett Dome is located in northern Semple Township and, therefore, was part of this year's mapping. The Halliday Dome covers most of Semple and Hutt townships (*see* Figure 5.1). The stratigraphy is interpreted by previous authors to be continuous from the Bartlett Dome to the Halliday Dome. The Bartlett Dome is bounded by the Kenogamissi batholith to the west, the Shaw Dome to the north, the Halliday Dome to the south and is unconformably overlain by Proterozoic Huronian Supergroup metasedimentary rocks to the east (Gowganda Formation). The Halliday Dome is bounded to the west by the Kenogamissi batholith, to the north by the Bartlett Dome and is unconformably covered to the south and east by rocks of the Proterozoic Huronian Supergroup.

The Archean supracrustal rocks in the Bartlett Dome area are composed of a lower sequence of mafic and ultramafic metavolcanic rocks with rare felsic metavolcanic rocks; a central sequence of intermediate to felsic metavolcanic rocks with regionally extensive metasedimentary units; and an upper sequence of mafic and ultramafic metavolcanic rocks with lesser intermediate to felsic metavolcanic rocks and semi-continuous metasedimentary rocks. The volcano-sedimentary rocks are intruded by large felsic intrusions (e.g., Adams pluton, Geikie pluton and the Kenogamissi batholith) and other smaller intrusions, ranging in composition from ultramafic to felsic. Proterozoic diabase dikes are attributed to the Biscotasing, Sudbury and Matachewan swarms.

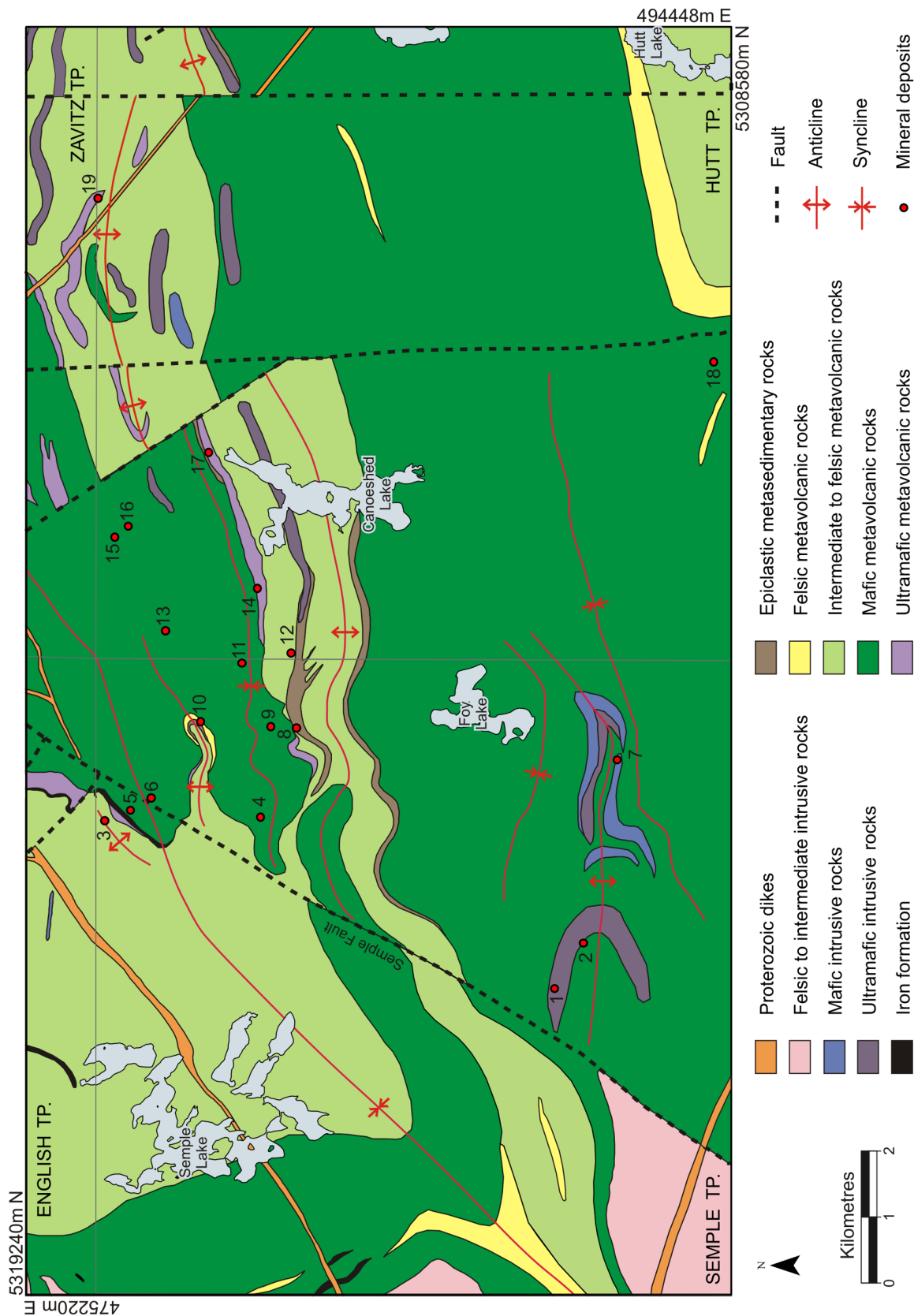
The Archean supracrustal rocks of the Halliday Dome are not as well defined; however, the stratigraphy from the Bartlett Dome can be correlated with the northern part of the Halliday Dome. Future bedrock mapping (summer 2010) and it is hoped geochronology will elucidate the stratigraphy of the Halliday Dome.

## **GEOLOGY OF SEMPLE AND HUTT TOWNSHIPS**

The geology of Semple and Hutt townships is dominated by mafic metavolcanic flows, both pillowed and massive, and fragmental units. The intermediate to felsic metavolcanic rocks are composed mainly of fragmental rocks such as tuff, lapilli tuff and tuff breccia, with minor massive flows located in the central and northern parts of the map area. Minor amounts of these lithological units are also found in southern Semple and Hutt townships. Metasedimentary rocks represent a minor component of the rocks in the current study area; they are mostly located in the central part of the map area. Minor ultramafic metavolcanic rocks are also observed, in the central part of the map area as well as the northern part of Hutt Township. Ultramafic intrusions are spatially associated with the ultramafic metavolcanic rocks. Minor mafic to ultramafic intrusions are found in the southern part of Semple Township. The Archean rock units within the map area have been complexly folded and faulted and are crosscut by Proterozoic diabase dikes of the Biscotasing and Sudbury swarms.

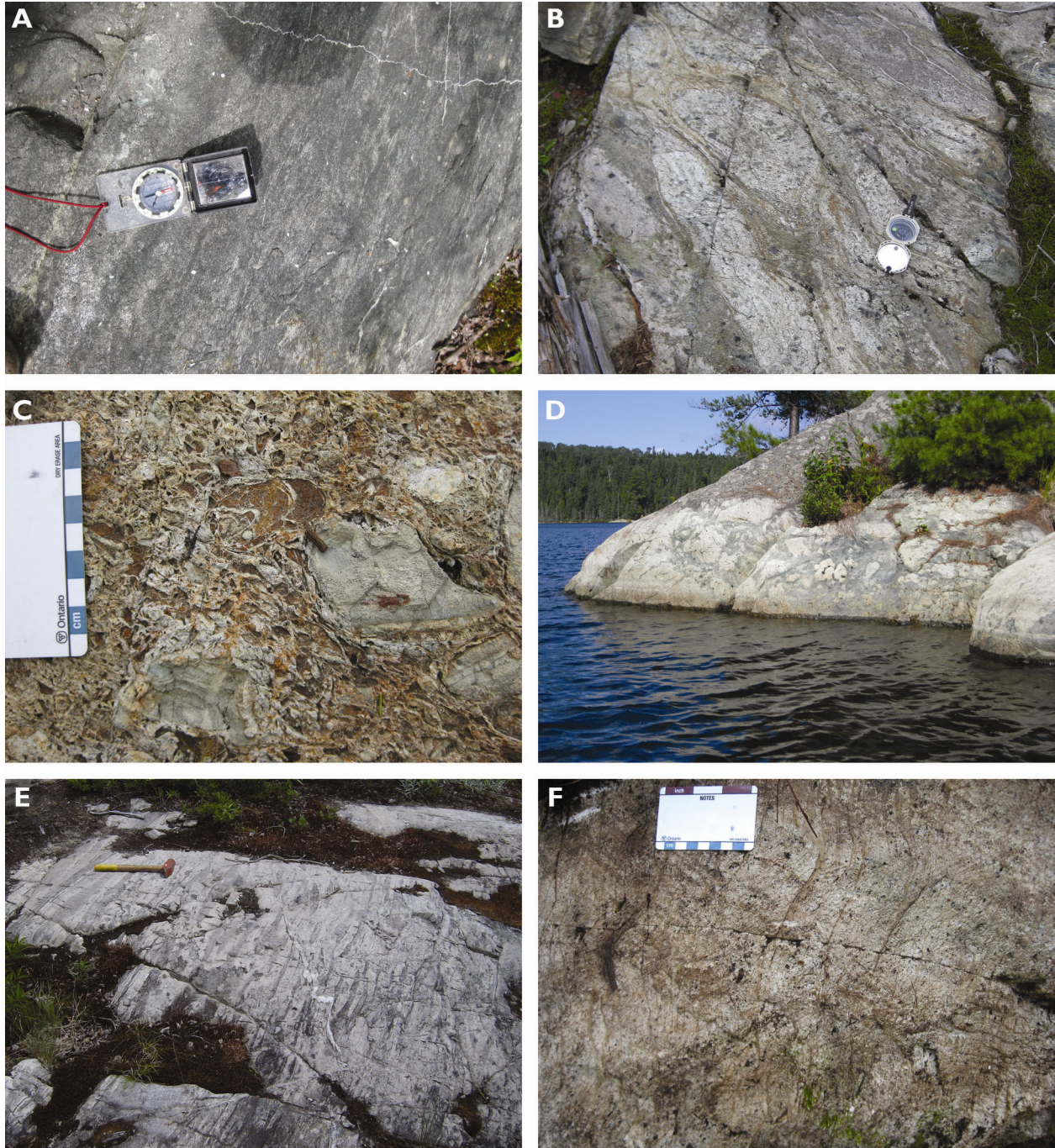
### **Mafic Metavolcanic Rocks**

The mafic metavolcanic rocks located in the western part of Semple Township and the eastern part of Moher Township are dominated by massive flows that are dark grey on the fresh surface and often recrystallized. As a result of deformation and contact metamorphism proximal to the Kenogamissi batholith, the mafic metavolcanic rocks are generally amphibolitized, lacking in primary features and exhibit a well-developed foliation (Photo 5.1A). Commonly within the map area, there is an intercalation of fine-grained and mylonitized mafic metavolcanic rocks and medium-grained, highly foliated gabbroic rocks, crosscut by felsic dikes.



**Figure 5.2.** Simplified lithostructural map of Hutt and Semple townships, south of Timmins, Abitibi greenstone belt. The southern portions of English and Zavitz townships are also included on the map. Mineral deposit numbers in Semple and Hutt townships refer to mineral deposit inventory occurrences (“ID”) listed in Tables 5.1 and 5.2, respectively.

The mafic metavolcanic rocks just east of the Semple fault (Figure 5.2), in the central part of Semple Township, are dominated by massive and pillowed flows. Both massive and pillowed flows are moderately to strongly foliated with pervasive iron carbonate alteration, making facing determination difficult (Photo 5.1B). The elongated pillows have moderate aspect ratios (4:1 width to thickness; on



**Photo 5.1.** A) Amphibolitized mafic volcanic rocks exhibiting a well-developed foliation. B) Moderately foliated pillowed flow. C) Fragmental facies of mafic metavolcanic rocks (hyaloclastite and pillow breccia), southern part of Hutt Township. D) Tuff breccias and pillowed flows, southeastern edge of Hutt Township. E) Interlayered amphibolitized mafic metavolcanic rocks and gabbros and intermediate volcanic rocks, southwestern edge of Semple Township. F) Intermediate to felsic metavolcanic rocks, west of the Semple fault.

average 1 m wide by 0.25 m in thickness) and commonly exhibit varioles at the margins of the pillows. Hyaloclastite is locally preserved; however, most of the interpillow material is preferentially affected by the deformation and, thus, is usually more altered than the pillows.

The mafic metavolcanic rocks located in the northern part of the map area are either massive or pillowed. The massive flows are generally homogenous and typically fine grained, but can display medium- to coarse-grained texture locally. The pillowed flows have well-developed pillows that vary in size from a few decimetres to a few metres in diameter. They are usually variolitic, vesiculated or amygdaloidal. The varioles are generally most abundant toward the margins of the pillows. Massive flows are rarely variolitic. Remnants of hyaloclastite are visible within the interpillow material in the less deformed areas.

The southern part of the map area is composed primarily of mafic metavolcanic rocks with minor felsic metavolcanic rocks. The mafic metavolcanic rocks are dominated by fragmental facies (hyaloclastite and pillow breccia) with minor pillowed and massive flows. The hyaloclastite is composed of vitric angular fragments ranging from a few millimetres to a maximum of 20 cm in diameter (Photo 5.1C). This unit can be several tens of metres thick. Pillow breccia and pillowed flows are commonly associated with the hyaloclastite. The pillows vary from 30 cm to over several metres in length and are commonly variolitic at the rims. The pillows are poorly developed, making top directions difficult to determine. However, rare, well-formed pillows in southern Semple Township indicate top reversal. Pillow selvages are dominated by hyaloclastite similar to that described above and, locally, disseminated pyrite is observed. The massive mafic flows vary in grain size from fine to medium grained and locally have patchy magnetite alteration, resulting in varying magnetic susceptibility readings. Both massive and pillowed flows are vesiculated and amygdaloidal, with vesicles and/or amygdules comprising up to 30% of the rock. Locally, a transition from massive flow to pillow breccia to pillowed flows was observed, as well as a transition from hyaloclastite to massive flows. In the very southeastern portion of Hutt Township, the rock types vary from mafic metavolcanic to intermediate metavolcanic. They are composed of tuff breccias and massive to pillowed flows (Photo 5.1D). The tuff breccia varies from monomictic to polymictic, with mafic to felsic volcanic fragments in an intermediate tuffaceous matrix. The pillowed and massive flows are generally more mafic in composition. The pillows are large and poorly formed. Throughout this package of rocks, minor felsic massive flows were observed, often bearing quartz eyes, as well as medium-grained gabbros, locally displaying feldspar glomeroporphyritic texture.

## Intermediate to Felsic Metavolcanic Rocks

Intermediate to felsic metavolcanic rocks dominate the southeastern limb of the syncline located west of the Semple fault (described in “Megastructures”) and are intercalated with mafic metavolcanic rocks on the northwestern limb of the fold. They generally comprise tuff to lapilli tuff, with rare massive units. The matrix of the lapilli tuff is aphanitic to fine grained and displays a light grey colour on the fresh surface and is white on the weathered surface. The tuff contains white fragments ranging in size from 0.2 to 0.7 cm. No sorting was observed. The massive units are aphanitic and quartz phenocrysts are locally present. The quartz phenocrysts are generally small, usually less than 0.5 cm in size. At the outcrop scale, most of the rocks in this package are interlayered with amphibolitized mafic metavolcanic rocks and gabbros (Photo 5.1E). Both the intermediate to felsic rocks and the amphibolitized mafic rocks are strongly deformed.

The intermediate to felsic metavolcanic rocks located to the west of the Semple fault are poorly exposed and are dominated by lapilli tuff that is strongly foliated and often referred to as a schist (Photo 5.1F). The weathered surface of these tuffs is generally a mottled white, grey or light grey-green colour, and the fresh surface is light to medium grey-green. The matrix is aphanitic to fine grained with elongated lapilli ranging from 0.2 to 6 cm in length. The lapilli are lighter coloured than the finer grained matrix and are locally angular. In the northern part of Semple Township, hydrothermal alteration and deformation is

locally intense and primary textures are difficult to see. The alteration is composed of chlorite and iron carbonate with minor sericite and hematite and is generally pervasive to selectively pervasive. The few outcrops encountered are located near the hinges of folds and display parasitic folding.

On the eastern side of the Semple fault, the majority of the intermediate to felsic metavolcanic rocks are composed mainly of volcanoclastic rocks such as lapilli tuff, crystal tuff and tuff breccia, with lesser amounts of massive flows. The lapilli tuff is generally monolithic, massive and well sorted, whereas the tuff breccia is polymictic (mostly intermediate to felsic fragments that range in size from a millimetre to several centimetres), matrix supported, massive and moderately well sorted (Photo 5.2A). The massive flows are generally more felsic in composition and locally display quartz phenocrysts ranging in size from 0.2 to 1 cm. Bedding is rarely observed.

## Chemical Metasedimentary Rocks

Four outcrops of iron formation were observed in the western part of Semple Township. Three of the outcrops are dominated by shales and chert, with minor amounts of magnetite-rich layers and minor sulphides, such as pyrite. The bedding and lamination in these outcrops varies from a few millimetres to several centimetres in thickness. The fourth outcrop has decimetre-scale magnetite-rich layers intercalated with shales and rare cherts. All of the outcrops display isoclinal folding.

Three outcrops of iron formation were observed north of Semple Township. The unit is dominated by magnetite-rich and lean oxide-facies iron formation, with lesser sulphide-facies iron formation interlayered with chert and clastic sediments, such as wackes and argillites (Photo 5.2B). This unit displays upright folding, and parasitic folds are commonly observed.

## Clastic Metasedimentary Rocks

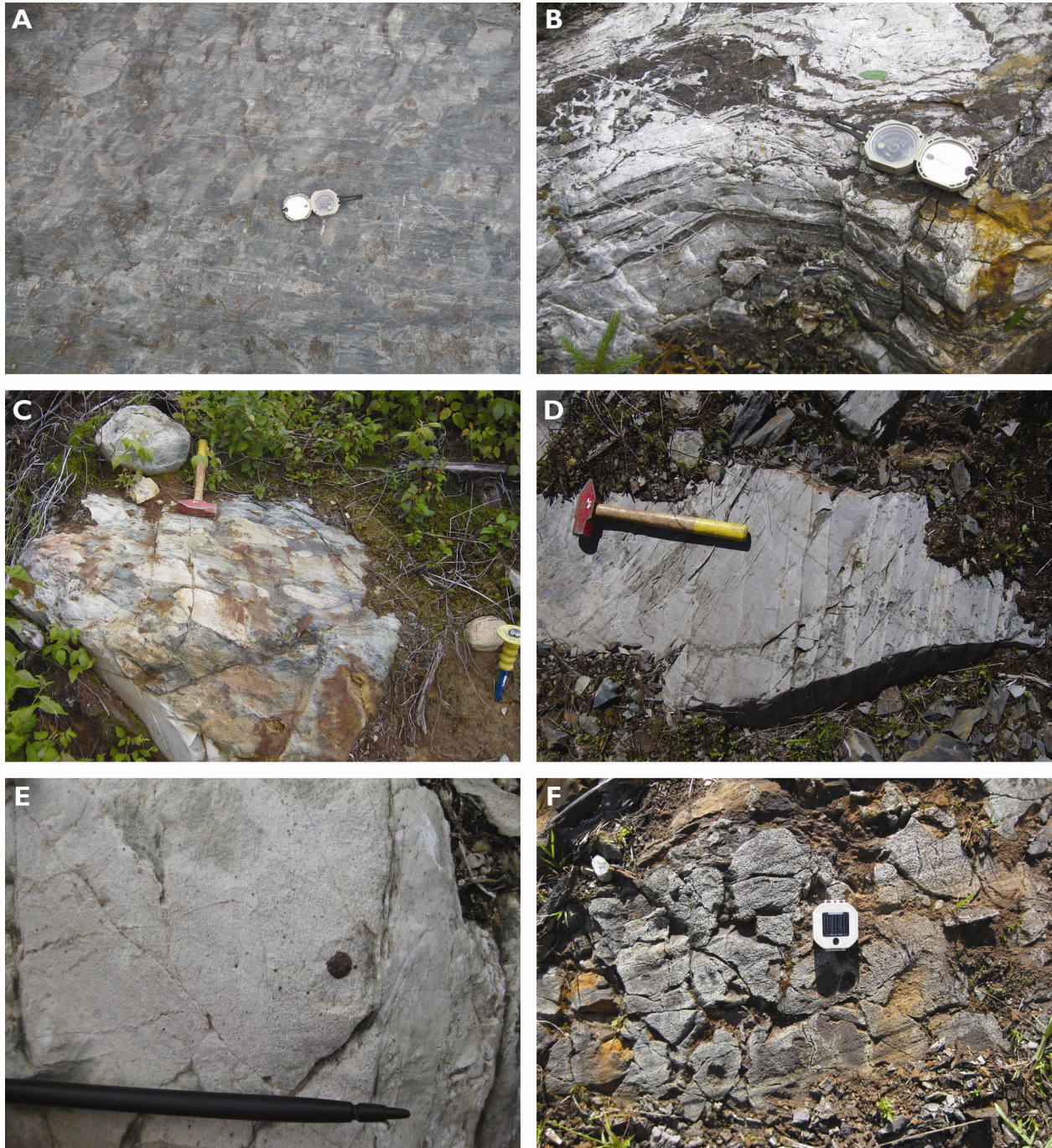
Several outcrops of clastic metasedimentary rocks were observed in the north and central parts of Semple Township and locally in the central part of Hutt Township. These rocks vary in facies from conglomerate, sandstone and siltstone to argillite. The conglomerates are concentrated in the north-central part of the map area near the boundary between Semple and Hutt townships. They are polymictic, with fragments that are subangular to rounded and vary from granule to boulder size (Photo 5.2C). The clast composition is dominantly volcanic, ranging from mafic to felsic in composition, with rare sandstone, argillite and sulphide fragments. Generally, the conglomerates are matrix supported with a pale green to white silty to sandy matrix.

Sandstone and siltstone are closely associated with the conglomerate. They generally have well-defined bedding varying from a few centimetres to a few decimetres in thickness (Photo 5.2D). The weathered surface is beige to pink in colour and the fresh surface displays darker tones but similar colour. The pink colouration is due to pervasive hematite alteration. Grading, cross-bedding and scours are locally observed and define good tops. These units are often associated with intermediate to felsic volcanoclastic rocks such as reworked tuff, lapilli tuff and tuff breccia.

Argillites are located in the central to northern part of the map area, near the border between Semple and Hutt townships. They are commonly laminated and interlayered with other clastic sediments and intermediate to felsic volcanoclastic rocks. They are generally green to dark grey in colour and are silicified.

The intermediate to felsic volcanoclastic rocks interlayered with the clastic and chemical metasediments are beige to pale green in colour. They vary from tuff and lapilli tuff to tuff breccia. The

tuff (Photo 5.2E) and lapilli tuff display rare bedding on a centimetre to decimetre scale with local graded bedding observed. The tuff breccia is generally massive, with heterolithic subangular to subrounded fragments ranging from a few centimetres up to 20 cm in size within a tuffaceous matrix.



**Photo 5.2.** A) Matrix-supported, massive and moderately well-sorted polymictic tuff breccia (mostly intermediate to felsic fragments); located on the east side of the Semple fault. B) Magnetite-rich and lean oxide-facies iron formation interlayered with chert; located in the northeastern corner of Semple Township. C) Polymictic conglomerate, with subangular to rounded fragments; located in the north-central part of the map area near the boundary between Semple and Hutt townships. D) Well-bedded sandstone and siltstone interbedded with the conglomerates shown in Photo 5.2C. E) Locally bedded intermediate to felsic volcanoclastic rocks. They are interlayered with the clastic and chemical metasedimentary rocks shown in Photo 5.2D. F) Ultramafic metavolcanic rocks displaying polygonal jointing; located in the northern part of Hutt Township.

## Ultramafic Metavolcanic Rocks

The ultramafic metavolcanic rocks are poorly exposed and are located in the northern part of the map area. They are dominated by thin, discontinuous flows. Within the massive flows, polygonal jointing (Photo 5.2F) and rare spinifex texture were observed, but “classical” komatiite flows with all internal subdivisions as defined by Pyke, Naldrett and Eckstrand (1973) were not seen. Thicker komatiite flows are generally characterized by cumulate texture comprised of olivine pseudomorphs. The ultramafic metavolcanic rocks in the map area are commonly strongly altered by magnesite, iron carbonate and fuchsite, giving the rocks a pale green-grey colour on fresh surfaces.

## Archean Mafic to Ultramafic Intrusions

Ultramafic intrusions located in northern Hutt Township have limited exposure and are mostly identified based on their geophysical signature, which is similar to the signature of the ultramafic intrusions found in the southern part of Zavitz Township and the ultramafic rocks found in drill core in Montrose Township. The intrusions are generally massive, homogenous, serpentinized cumulate and commonly display the fracture pattern associated with serpentinization.

In the southern part of Semple Township, mafic to ultramafic intrusions define an anticlinal fold closure (*see* Figure 5.2). The westernmost of these intrusions was only observed in 2 outcrops and, thus, its distribution is mostly inferred from geophysical signatures. It is a massive, homogenous, medium-grained, serpentinized, cumulate ultramafic rock. The eastern intrusion is a layered intrusion of peridotite to gabbro. The ultramafic portion is composed of medium- to coarse-grained serpentinized cumulate, which is dark green to blue-grey in colour. The contact between the ultramafic component and the gabbro component is gradational. The gabbro is medium to coarse grained, massive and homogenous.

## Archean Intermediate to Felsic Intrusions

The Kenogamissi batholith is a large, composite tonalitic to granitic felsic intrusion (*see* Houllé, Baldwin and Thurston 2008). The eastern margin of the Kenogamissi batholith, located in the southwest corner of Semple Township, is dominated by fine- to medium-grained granodiorite to diorite that exhibits a light grey-pink to light red weathered surface, reflecting the level of hematization of the rocks, and a light grey to pinkish colour on fresh surfaces. This intrusion generally exhibits an equigranular to locally slightly porphyritic texture.

## Proterozoic Intrusions

The Proterozoic diabase dikes observed in the map area are attributed to the Biscotasing and Sudbury swarms. The Biscotasing dikes define a northeast trend and are observed in the northwestern part of Semple Township. They consist of leucocratic, medium- to coarse-grained, ophitic-textured, hematized quartz gabbro to diorite dikes. They are moderately magnetic and typically show a distinct geophysical signature. No outcrop of the Sudbury swarm was observed in the map area; however, based on previous mapping and the geophysical signature associated with the Sudbury dike swarm, the northeastern part of Hutt Township appears to be crosscut by one of these gabbro dikes. The dikes commonly follow pre-existing structures and zones of weakness, but are locally observed to bifurcate.

## STRUCTURAL GEOLOGY

The deformation is highly heterogeneous throughout the map area. All lithologies are affected by shear zones on a scale of metres to tens of metres in width, alternating with zones of little to no deformation. The maximum intensity of the deformation was seen on the eastern side of the Kenogamissi batholith (in Semple Township) and at the boundary between Supracrustal Packages B and C previously defined (Houlé 2007; Houlé and Solgadi 2007; Houlé, Préfontaine and Brown 2008; Houlé, Solgadi and Préfontaine 2009; *see* "Preliminary Interpretations"). The metamorphic grade associated with the deformation reaches amphibolite facies along the eastern boundary of the Kenogamissi batholith and decreases to greenschist facies further east.

### Megastructures

The major structural feature seen in the map area is the rotation of the regional composite fabric (bedding, foliation and parasitic folds) from north-trending along the Kenogamissi batholith to east-trending in the east parts of Semple and Hutt townships. This inflection is likely accommodated by kilometre-scale upright folds that display a rotation of their axis azimuths from northeast-trending in the west to more east-trending in the east. The transition zone occurs in the northeast corner of Semple Township.

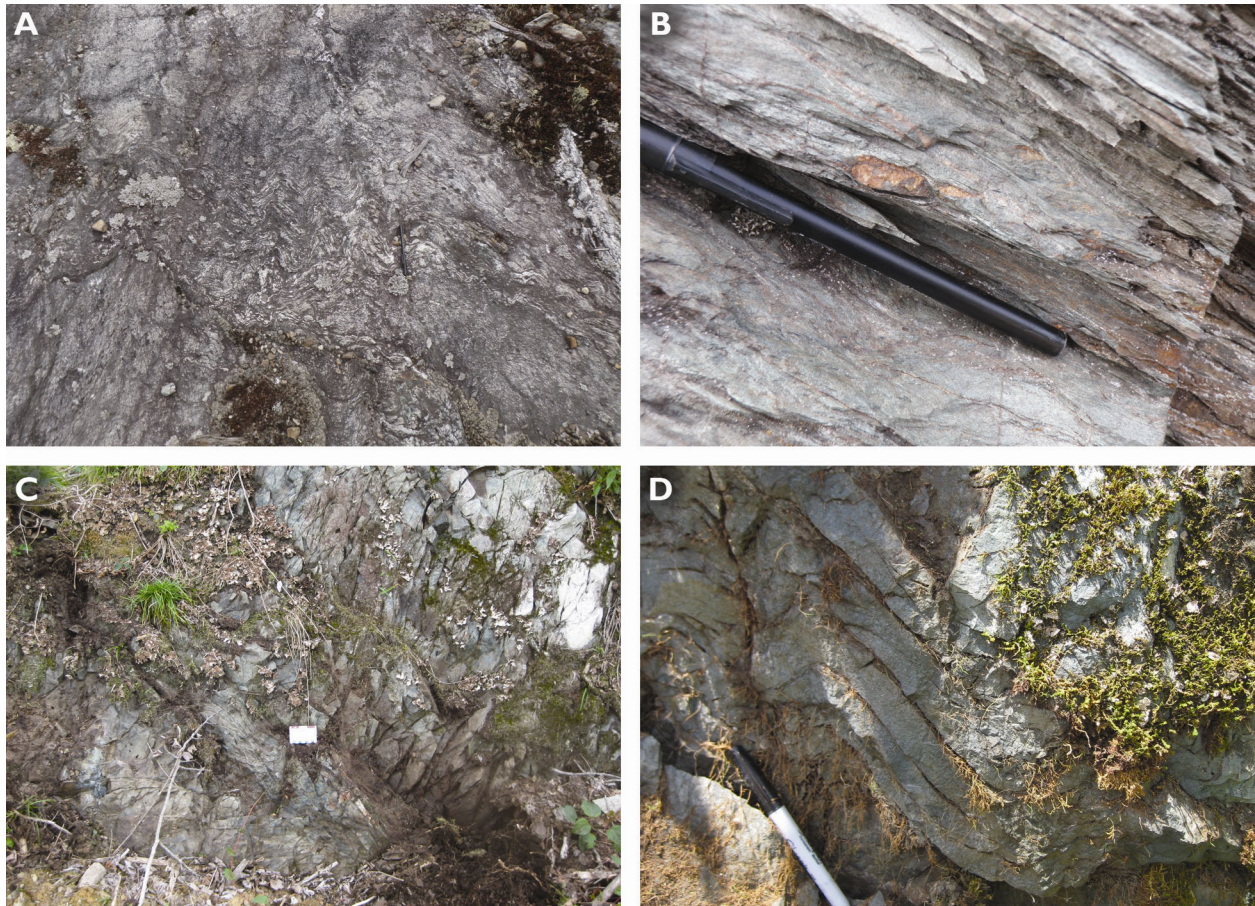
The most conspicuous of these upright folds is a syncline, based on top reversals of pillows in Zavitz Township, extending from the southwest to the northeast corner of Semple Township. The hinge of this fold displays an average plunge of 30° to the northeast. The fold continues into Zavitz Township, where it is rotated clockwise to a more easterly trend (Houlé, Baldwin and Thurston 2008). In Semple Township, the fold deforms an earlier mylonitic foliation (*see* "Microstructures (Early Deformation)"). Conspicuous parasitic M, Z and S folds, displaying plunges ranging from 20 to 50° to the northeast, are observed along the hinge of this fold (Photo 5.3A). This folding may locally be responsible for the development of crenulation cleavage parallel to the axial plane of the syncline.

Other major folds are observed in the area. These folds are non-cylindrical, and periclinal terminations are common. At least 2 syncline–anticline pairs have been found. Their axes display a transition from a northeast trend in the northwest part of the study area, to an east trend in the southeast. Their existence is interpreted from top reversals of various top indicators such as pillows in basalts, graded and cross-bedding in sediments and volcanoclastic rocks, and subsidiary structures such as M, S and Z folds. Towards the southeast part of the map area, the subsidiary structures (parasitic folds) become less prominent, possibly due to the nature of the rocks (massive to pillowed mafic metavolcanic rocks are typically not good units for recording moderate deformational strain). The intermediate metavolcanic rocks in the central part of Semple Township and northern part of Hutt Township define a major anticline.

Heading east, this anticline is likely faulted in a sinistral offset by late north- to northwest-trending brittle faults. The eastern part of this anticline trends east and lies along both the north part of Hutt Township and the south part of Zavitz Township. The core of this anticline is occupied by felsic to intermediate metavolcanic rocks intruded by ultramafic sills. The komatiites and associated sediments underlying the boundary between Supracrustal Packages B and C defined previously (Houlé, Baldwin and Thurston 2008; Houlé and Solgadi 2007) delineate the outer rim of this dome.

## Microstructures (Early Deformation)

Most microstructures are related to an early event that is characterized by coaxial and non-coaxial deformation responsible for the mylonitization of various lithologies. This deformation preferentially seems to affect the lithological boundaries. Nevertheless, though this fabric is continuous on the eastern boundary of the Kenogamissi batholith, it becomes less prominent in the east part of the study area, where foliation becomes weak. This apparent lack of continuity may be due to various reasons, such as a real discontinuity and/or a lack of outcrop in key areas. The original trend of the foliation ( $S_1$ ) is difficult to assess due to the strong overprinting by later folding. Nevertheless, it is likely that this  $S_1$  foliation was subhorizontal, since it is parallel to the volcanic–sedimentary bedding on a regional scale. Locally, stretching and mineral lineations were observed associated with this foliation. These lineations plunge down-dip to the east along the Kenogamissi batholith and to the northeast in the north part of Semple Township. The only shear criterion that was observed displays northeast-side-down shearing and is located in the northwest corner of Hutt Township (Photo 5.3B). Further investigation of oriented hand samples will be necessary to obtain reliable information on the kinematics of the shearing.



**Photo 5.3.** A) M folds refolding a previous  $S_1$  mylonitic foliation (hinge of the regional northeast-trending syncline). A crenulation cleavage parallel to the axial plan of the fold is locally present (bottom left of the photo). Location is in northeastern Semple Township; photo is looking northeast. B) Asymmetric boudinage of quartz vein and shear bands giving a northeast-side-down apparent movement. The view is perpendicular to the  $S_1$  foliation and parallel to the stretching lineation, shown in the top right corner of the photo. C) Late decimetre-scale shear zone crosscutting at a high angle the previous regional fabric in mafic volcanic rocks; located in the southeastern portion of Hutt Township. Photo is looking northwest. D) Northwest-trending upright fold within the mafic volcanic rocks located in the southeastern portion of Hutt Township. Photo is looking northwest.

## Late Structures

Late structures in the map area are characterized by buckling, both of the previous mylonitic fabric ( $S_1$ ) and the upright folding. The axial planes of these late, tight to open folds trend north to northwest. This last folding event is only visible on a regional scale and is indicated by the disturbance of the regional composite fabric. Very few microstructures are associated with these folds. Two microstructures were found southeast of Hutt Township, namely a 30 cm wide shear zone (Photo 5.3C) and a northwest-trending decimetre-scale upright fold (Photo 5.3D).

The map area was also affected by late brittle faulting. Field evidence to substantiate this faulting event is rare and only mapping and geophysical interpretation brings some clues. The Semple fault trends northeast, following the trend of the regional syncline described above (*see* “Megastructures”) and corresponds on the magnetic map to a conspicuous lineament. Little or no strike-slip offset is observed at map scale. On the basis of lithologic arguments (younger rocks to the east), an east-side-down movement is inferred for the Semple fault. Another major brittle fault is present in Hutt Township, trending north and displaying a sinistral strike-slip movement. The presence of this fault is inferred by the offset of high magnetic anomalies. The fault appears to die out to the north: its real extension is still under investigation.

## Structural Interpretation

The geodynamic context that resulted in the mylonitic foliation ( $S_1$ ) in the study area is still in question. It might be related to early flat-lying thrusting in a transpressive context. The late upright folding is likely coeval with regional doming. Both domes and upright folds display the same regional trend. No overprinting relationships between domes and folds have been observed. Triple points are commonly observed when the 2 types of structures merge. The regional syncline described in a previous section (*see* “Megastructures”) marks the boundary between 2 major structures: the Halliday Dome to the south and the Bartlett Dome to the north. The northeast trend of this syncline in the southwest part of the map area may also be related to the Larder–Cadillac shear zone to the south, which displays the same northeast trend.

## PRELIMINARY INTERPRETATIONS

Studies carried out during previous years defined supracrustal packages that could be delineated through several townships (Houlé 2007; Houlé and Solgadi 2007; Houlé, Préfontaine and Brown 2008; Houlé, Solgadi and Préfontaine 2009); however, due to the structural complexity in Hutt and Semple townships, these supracrustal packages could only be correlated over a limited area.

The largely mafic metavolcanic sequence located west of the Semple fault is interpreted to be the southern extension of previously defined Supracrustal Package A observed in Bartlett and English townships (Houlé and Solgadi 2007; Houlé, Préfontaine and Brown 2008; Houlé, Solgadi and Préfontaine 2009). It is bounded to the west and south by the Kenogamissi batholith, to the north by Supracrustal Package B and to the east by the Semple fault. In general, Supracrustal Package A is dominated by massive and pillowed mafic metavolcanic flows with lesser amounts of intermediate metavolcanic rocks and chemical sediments, all of which are crosscut by felsic and mafic dikes and intrusions. Geochronology results from a felsic tuff unit within the lowermost part of the succession in Bartlett Township yielded a U/Pb age of  $2728.3 \pm 1.6$  Ma (Houlé, Baldwin and Thurston 2008) constraining it to the Deloro assemblage.

The sequence of intermediate rocks west of the Semple fault, in the northern part of Semple Township, has similar features to previously described Supracrustal Package B (Houlé and Solgadi 2007; Houlé, Préfontaine and Brown 2008; Houlé, Solgadi and Préfontaine 2009). It is bounded to the west and south by Supracrustal Package A and to the east by the Semple fault. Supracrustal Package B is poorly exposed, with extensive Quaternary cover. It is dominated by fragmental rocks of intermediate to felsic composition overlain by ultramafic rocks and metasediments, with few felsic dikes crosscutting the units. This package is assigned to the younger parts of the Deloro assemblage (*circa* 2724 Ma) based on U/Pb ages obtained in McArthur and Bartlett townships (Houlé, Baldwin and Thurston 2008).

East of the Semple fault, stratigraphic correlation is more nebulous. The sequence of dominantly mafic metavolcanic rocks located in the northern section of the map area at the boundary of Semple and Hutt townships is interpreted to be part of previously defined Supracrustal Package C (Houlé and Solgadi 2007; Houlé, Préfontaine and Brown 2008; Houlé, Solgadi and Préfontaine 2009). Supracrustal Package C is dominated by mafic metavolcanic rocks with minor komatiite and komatiitic basalt, as well as intermediate to felsic metavolcanic rocks. A U/Pb age of  $2708 \pm 1.2$  Ma for a felsic volcanoclastic rock in northwestern Hutt Township (Ayer et al. 2002; Ayer, Ketchum and Trowell 2002) suggests that most of this package is best assigned to the Tisdale assemblage.

Underlying the mafic to ultramafic rocks (Supracrustal Package C) are metasedimentary rocks. Three outcrops of iron formation were mapped during the current study in the northern part of Semple Township. These iron formations may be correlated with the upper iron formation of Supracrustal Package B (Deloro assemblage), or the base of the mafic sequence of Supracrustal Package C (Tisdale assemblage).

The upper horizon of iron formation in Supracrustal Package B is located at the boundary of Supracrustal Packages B and C, which is consistent with what was observed in northern Semple Township. It was previously described as a unit dominated by magnetite-rich and lean oxide-facies iron formation with minor sulphide- and carbonate-facies iron formation and chert breccia occurring more sporadically within this horizon. Felsic heterolithic volcanoclastic rocks, fine-grained sandstone, siltstone, pebble conglomerate and wacke are locally intercalated with the iron formation (Houlé, Baldwin and Thurston 2008). In comparison, the iron formation in the northern part of Semple Township is chert-rich oxide- and sulphide-facies iron formation interlayered with minor clastic sediments.

Clastic metasedimentary rocks are also found underlying the mafic and ultramafic rocks of Supracrustal Package C. These may be interpreted as a lateral variation of the chemical sediments, thus assigning them to the Deloro assemblage. They are located stratigraphically at the same horizon as the iron formation and are interlayered with felsic volcanoclastic rocks. They are found on either side of the anticline located in the central part of the map area (*see* Figure 5.2). Considering the potential lateral correlation with the iron formation, the clastic metasedimentary rocks may be interpreted to be within the upper units of the Deloro assemblage.

On the other hand, minor iron formation is observed in the Tisdale assemblage. A sample of heterolithic tuff breccia collected in the footwall of the Adams Mine in Boston Township yielded a U/Pb age of  $2712 \pm 4$  Ma likely putting it within the lower Tisdale assemblage (Ayer et al. 2002). The iron formation at the Adams Mine is located at the base of the Tisdale assemblage associated with mafic and ultramafic metavolcanic rocks. Within the map area, the above-mentioned iron formations underlie ultramafic metavolcanic rocks, which can also be found at the base of the Tisdale assemblage. The metasedimentary rocks in the current map area are similar to those observed in Bannockburn Township (Préfontaine and Berger 2005), suggesting a possible correlation between these metasedimentary units with the metasedimentary rocks in northern Bannockburn Township. A conglomeratic unit in Bannockburn Township yielded a maximum U/Pb age for deposition of  $2705 \pm 2$  Ma (Berger, Préfontaine and Ayer 2007).

The intermediate to felsic metavolcanic rocks located on the eastern side of the Semple fault have a more uncertain timing. They may be considered to belong to the upper part of the Deloro assemblage (Supracrustal Package B) or to the base of the Tisdale assemblage (Supracrustal Package C). It is also possible that both Deloro and Tisdale assemblages are present in this sequence of volcanoclastic rocks.

The mafic metavolcanic rocks located in the core of the anticline east of the Semple fault in the central part of the map area, have poor geochronological constraints. They may be as young as the Tisdale assemblage, assuming that, below the base of the calc-alkalic intermediate metavolcanic rocks, there is a sequence of mafic metavolcanic rocks. However, considering that no mafic metavolcanic rocks have been previously described underlying the intermediate metavolcanic rocks at the base of the Tisdale assemblage, the probability of these mafic metavolcanic rocks being part of the Tisdale assemblage is low. Consequently, these rocks must be older than the Tisdale assemblage. The preferred interpretation is that this sequence of rocks is part of the Deloro assemblage, although one cannot exclude the possibility that they may be part of the Kidd–Munro, Stoughton–Roquemaure or Pacaud assemblages.

The southern part of Hutt and Semple townships is interpreted to be part of the Tisdale assemblage, based on a U/Pb age of  $2710.5 \pm 1.6$  Ma from a rhyolite flow in Midlothian Township. This package of rocks may be considered to be at least contemporary with Supracrustal Package C (Houlé, Baldwin and Thurston 2008; Houlé and Solgadi 2007).

## ECONOMIC POTENTIAL

A variety of commodities have been reported in Semple and Hutt townships, based on past bedrock mapping and mineral exploration programs by mining companies and prospectors. A total of 19 mineral deposit inventory (MDI) sites are reported in the map area, widely distributed throughout the area (*see* Figure 5.2); however, most of these report only marginal assay values. Tables 5.1 and 5.2 summarize the known mineral occurrences in Semple and Hutt townships.

The mineral deposit inventory data and the bedrock mapping highlight several commodities in the map area. The dominant commodities are gold, nickel and base metals (copper and zinc). Minor amounts of lead, silver, cobalt and asbestos were also reported, as well as one significant value for platinum.

Gold mineralization in Semple and Hutt townships is located in the northern part of the map area at the border of the 2 townships. The mineralization is associated with mafic to intermediate metavolcanic rocks that are strongly altered by carbonate and chlorite and are generally crosscut by felsic intrusions and quartz veins. This area has a complex structural history. The gold mineralization here is similar to that described in English and Zavitz townships by Houlé, Baldwin and Thurston (2008).

Nickel, copper, platinum group element and asbestos mineralization is associated with ultramafic intrusions. Most of this type of mineralization is reported from the southern part of Semple Township, where it is associated with mafic to ultramafic intrusions. The only other occurrence of this type of mineralization is reported from the northern Hutt Township associated with an ultramafic intrusion. Based on bedrock mapping and geophysical signatures, other ultramafic intrusions and ultramafic metavolcanic units are likely to be found in the area, making the northern part of Hutt Township attractive for exploration.

Base metal mineralization (copper and zinc) occurs mainly in the northern part of the map area at the boundary of Semple and Hutt townships. This type of mineralization is hosted by several different lithologies; one occurrence was reported to be hosted in quartz veins. One exception is located in the southern part of Hutt Township where this type of mineralization is associated with FIII rhyolites (J.A. Ayer, personal communication, 2009), a rock unit that is commonly associated with volcanogenic massive sulphide deposits in the Superior Province (Leshner et al. 1986).

**Table 5.1.** Main characteristics of the Mineral Deposit Inventory sites in Semple Township. “ID” refers to locations on Figure 5.2.

Occurrence	ID	Commodities	Best Historic Value	Hosted Units
Parting Lake Property / Semple Township Group 1	1	Asbestos	up to 1/8 inch	Ultramafic intrusive within intermediate metavolcanic rocks
Daniel Mining DDH2 / Mining Corp. of Canada DDH2 / Serpentine Lake Property MDI41P14NW00010	2	Ni, asbestos, Cu, Pt	up to 0.41% Ni, asbestos width up to 1/4 inch, 2912 ppm Cu, 204 ppb Pt	Ultramafic intrusive (peridotite)
Foisey Property / Tri-Origin C Block MDI41A03SE00002	3	Au	up to 5.48 ppm Au	Sulphide-rich ironstone. Intermediate metavolcanic, quartz-feldspar porphyry and ultramafic metavolcanic rocks nearby
Northern Fe-carbonate Altered Zone / Triex DDH WRL 98-6 MDI41P14NE00061	4	Au	up to 0.87 g/t Au	Carbonatized mafic metavolcanic rocks. Lamprophyre and syenite dike nearby.
Tri-Origin DDH TE-98-07 MDI42A03SE00048	5	Au	up to 4663 ppb Au	Felsic alkalic intrusive. Foliated mafic metavolcanic rocks nearby.
Tri-Origin DDH TE-98-08 MDI42A03SE00047	6	Au	up to 6377 ppb Au	Quartz-carbonate mafic metavolcanic rocks cross-cut by felsic alkalic intrusion
Mustang Area 4 / Foy Lake Property MDI000000000438	7	Ni, (Cu, Co)	up to 0.14% Ni, (0.02% Cu, 0.010% Co)	Ultramafic intrusion within intermediate metavolcanic rocks
Duncan Zone MDI41P14NE00060	8	Cu	up to 5.12% Cu	Quartz veins within intermediate and mafic metavolcanic rocks
Saville Prospect / Glenburke Option MDI41P14NE00058	9	Au	up to 25.16 g/t Au	Quartz veins within intermediate metavolcanic rocks. Felsic intrusive rocks nearby.
Alford McCall / Decker Main Zone MDI42A03SE00008	10	Au	up to 7.14 g/t Au	Intermediate to felsic metavolcanic rocks cross-cut by quartz veins
ESSEX Mineral Hydro Block (DDH 79-8) MDI41P14NE00052	11	Zn, Cu, Au, (Ag)	up to 10450 ppm Zn, up to 2345 ppm Cu, up to 1.9 ppm Au	Graphitic tuff, intermediate tuff and lapilli tuff with quartz, carbonate, talc and chlorite alteration nearby

Source: Mineral Deposit Inventory (MDI2) recently updated by A. Wilson, Timmins Resident Geologist Office.

**Table 5.2.** Main characteristics of the Mineral Deposit Inventory sites in Hutt Township. “ID” refers to locations on Figure 5.2.

Occurrence	ID	Commodities	Best Historic Value	Hosted Units
Hutt / Hollinger Redstone River Group MDI41P14NE00027	12	Au	up to 0.34 g/t Au	Quartz veins within intermediate metavolcanic rocks
Hydro Gold Prospect MDI41P14NE00050	13	Au	up to 22.78 g/t Au	Sheared intermediate metavolcanic rocks
Green Carbonate Trench / Robert Sample 31939 MDI41P14NE00059	14	Au	2194 ppb Au	Quartz veins within a green carbonate in mafic and ultramafic rocks
BHP DDH 92EDH1 MDI42A03SE00009	15	Zn, (Cu), Au	up to 6400 ppm Zn, (1110 ppm Cu), 15 ppm Au	Sheared mafic metavolcanic rocks
Clayton-Cyr / Dowa Mining DDH5-1 / Essex Mineral Wicks Road Block MDI42A03SE000439	16	Ni, (Cu, Zn)	up to 0.22% Ni, (0.041% Cu, 0.15% Zn)	Carbonatized intermediate metavolcanic rocks
Inmet DDH Mat-02 / Matawest Property MDI42A03SE00033	17	Au	up to 0.67 g/t Au	Tonalite within mafic metavolcanic rocks
AMAX Exploration DDH KX8-67 / AMAX Adele Group MDI41P14NE00053	18	Cu, (Zn, Pb, Ag)	up to 3.74% Cu, (0.02% Pb, 0.04% Zn, 0.39 oz/t Ag)	Intermediate to felsic metavolcanic rocks
Rio Tinto- R&R Option DDH 8 MDI42A03SE00031	19	Ni	up to 0.11% Ni	Ultramafic intrusive within felsic metavolcanic rocks

Source: Mineral Deposit Inventory (MDI2) recently updated by A. Wilson, Timmins Resident Geologist Office.

## ACKNOWLEDGMENTS

This project has benefited from the assistance of Donald Bark, Kristin Henry and Sarah Jackson-Brown. Patrick Gervais is thanked for drafting and finalizing figures for this report. The authors appreciate all the support from the staff of the Timmins Resident Geologist Office (Ann Wilson, Diane Draper and Brian Atkinson). Michel Houlé is thanked for his insight, interpretation and discussions of the previously mapped area of the Bartlett Dome. Insightful discussions and comments from colleagues such as Ben Berger, John Ayer and Gary Beakhouse are greatly appreciated. Thanks are extended to Cindy, Ben and Roy of the Warne Logging and Sawmill tourist camp for their generous assistance during the field season.

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# 6. Project Unit 06-004. Scoping Study, Zinc Oxide Mineral Potential of the Northern Central Metasedimentary Belt, Grenville Province

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## INTRODUCTION

Traditionally, zinc exploration in marbles within the Central Metasedimentary Belt of the Grenville Province has focussed on traditional sulphide-hosted deposits, such as those mined at Balmat, New York and at Long Lake, Ontario (Figure 6.1). However, the world's largest non-supergene non-sulphide zinc deposits are also hosted in Grenvillian marbles located at Franklin and Sterling Hill in New Jersey; thus, the potential exists for both sulphide and non-sulphide zinc deposits within the Grenville Province in Ontario.

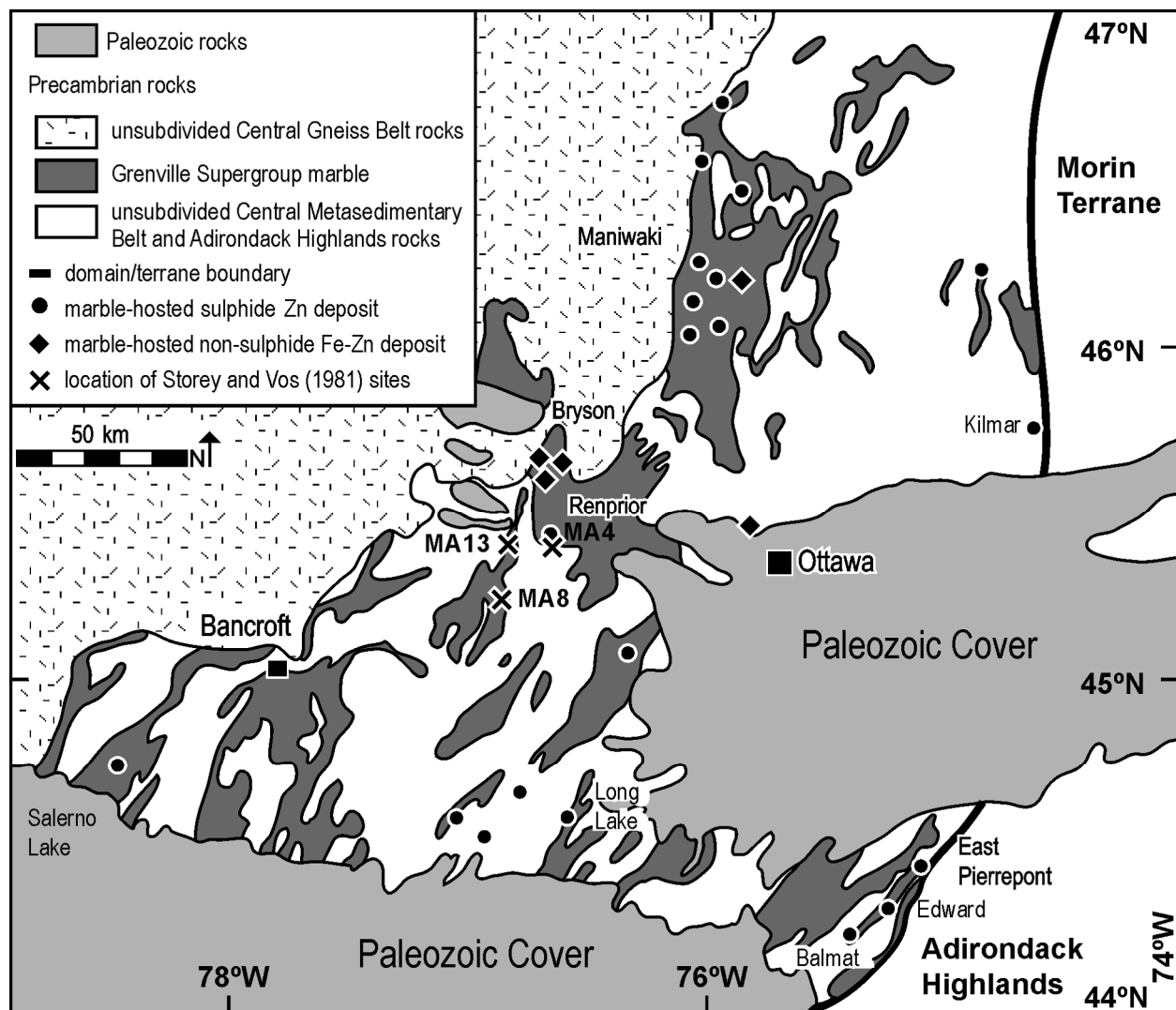
Recently, Gauthier and Larivière (2005) described the presence of zincian magnetite and silicate in dolomite marbles near Bryson, Quebec, approximately 60 km west of Ottawa, and 25 km north-northwest of Renfrew, Ontario. Gauthier and Larivière (2005) reported that the zincian content of the magnetite was related to dendritic exsolution of wurtzite, a low-temperature polymorph of sphalerite and that the zincian silicate was a serpentine containing up to 2 weight % ZnO. They also reported the presence, in zincian serpentine nodules, of fine inclusions of zincian pyrophanite ((Fe, Mg, Zn, Mn)TiO<sub>3</sub>), a rare zincian ilmenite known to occur in the Franklin–Sterling Hill district. Pyrophanite at Bryson contained up to 12 weight % ZnO (Gauthier and Larivière 2005).

In the Franklin–Sterling Hill district, wurtzite dendritic exsolutions have been described in spinel of the solid solution between magnetite and franklinite where they have been interpreted as an indication of retrograde destabilization of franklinite formed at granulite facies (Gauthier and Larivière 2005). Willemite (Zn<sub>2</sub>SiO<sub>4</sub>), the main ore-mineral in the Franklin–Sterling Hill deposits, has the same general formula as olivine ((Mg,Fe)<sub>2</sub>SiO<sub>4</sub>), except that the dominant cation is zinc instead of iron or magnesium. Thus, during retrograde metamorphism, the alteration of willemite will result in a serpentine-type mineral. Based on these mineralogical factors, Gauthier and Larivière (2005) concluded that the Bryson zincian magnetites and silicates are a retrograde equivalent of granulite-facies zinc oxide deposits, similar to those of the Franklin–Sterling Hill district.

Given the proximity of Bryson to the marble-rich Renfrew area, 2 weeks of the 2009 field season were spent sampling marbles in the northern part of the Central Metasedimentary Belt, from Gooderham to Tory Hill to determine if zinc oxide mineralization, similar to that described by Gauthier and Larivière (2005) for the Bryson area, might be present in Ontario.

## SAMPLING STRATEGY

Two regional marble sampling programs were undertaken by the Ontario Geological Survey in the Central Metasedimentary Belt in the 1970s and 1980s (Storey and Vos 1981; Grant, Papertzian and Kingston 1989) and served as a starting point for the scoping study. Consequently, sampling focussed on high metamorphic grade dolomite marbles in areas of the northern Central Metasedimentary Belt that were not covered by these studies (e.g., northern Monmouth Township, Wilberforce area) or in areas where either anomalous zinc values, serpentine minerals, or magnetite accumulations had been reported. In particular, the Storey and Vos (1981) detailed study areas MA4 (Ashdad–Renprior), MA8 (Centennial Lake) and MA13 (on Highway 41 west of Dacre) (*see* Figure 6.1) were examined in detail because of the presence of dolomite marbles and serpentine. Additional work at MA4 is discussed elsewhere (*see* Easton, this volume, Article 7). Samples were collected for assay, whole-rock geochemical and mineralogical examination.



**Figure 6.1.** Map showing the distribution of major marble belts within the Central Metasedimentary Belt and the Adirondack Lowlands, Ontario, New York and Quebec, and the location of zinc sulphide and zinc oxide deposits.

## PRELIMINARY RESULTS

Some preliminary chemical analyses and assay results were available at the time of writing. Despite containing visible sulphides, none of the assay samples contained any significant amounts of copper, lead or zinc. The whole-rock analyses confirmed the field classification of marbles as calcite, dolomite or as siliceous marbles. Eight samples, 3 of which were from Storey and Vos (1981) study area MA13, were clean; containing less than 3 weight % non-carbonate material.

All of the calcite marbles, with one exception, contain low total rare earth element contents with negative cerium anomalies. Negative cerium anomalies are characteristic of modern seawater (Flett 1984), and the preservation of negative cerium anomalies in the calcite marbles indicate that these samples have not undergone any significant trace element remobilization, such as which might occur during hydrothermal alteration, since original marine deposition. The exception is one sample in the Ashdad–Renprior area, which contained fine disseminated sulphides and smelled of sulphur when hammered. The absence of a negative cerium anomaly in this sample, as well as the presence of sulphides, suggests that this calcite marble may have been subjected to hydrothermal alteration. This sample was not anomalous with respect to lead or zinc, however.

Four samples of marble, all dolomite, were anomalous with respect to zinc. Two samples of serpentine-bearing dolomite marble from study area MA13 on Highway 41 contained 188 and 78 ppm Zn (samples 09RME-2017 and 09RME-2018, respectively). Sample 09RME-2017 was collected near Storey and Vos (1981) sample PM92, which contained 590 ppm Zn. Sample 09RME-2018 was collected near sample PM91, which contained 41 ppm Zn. Three of 4 dolomite marble samples from study area MA13, including sample 09RME-2017, show negative cerium anomalies, suggesting that these rocks have not undergone any significant hydrothermal alteration since original marine deposition. Except for one other dolomite marble sample collected near Centennial Lake, these were the only dolomite marbles which exhibited negative cerium anomalies. The fact that these samples contain zinc and serpentine, with no obvious sulphides, is consistent with the non-sulphide zinc model. Further work in the area of MA13 is needed in order to better understand the significance of both the zinc and rare earth element results.

The third anomalous zinc sample (09RME-2021), from the Ashdad–Renprior area (MA4), was a tremolite-bearing dolomite marble collected immediately south of the Flinton Group metapelitic rocks (*see* Easton, this volume, Article 7 for description). It contained 933 ppm Zn, 21 ppm Pb, and >4 ppm Cd. Storey and Vos (1981) also collected a sample (MA4-7) containing 1200 ppm Zn from the same outcrop area. The rare earth element pattern for this sample is similar to the post-Archean shale composite and the adjacent Flinton Group metapelites, and it is possible that this sample is a Flinton Group marble.

The fourth sample, a chondrodite-phlogopite-graphite dolomite marble collected on Highway 648 south of Wilberforce, contained 141 ppm Zn. Geochemically, this rock is a siliceous marble, and it is possible that the zinc content of this rock in part reflects the original clay mineral content of the rock, rather than resulting from mineralization.

Two samples were collected south of Bancroft in the vicinity of sample 864 of Grant, Papertzi and Kingston (1989), which contained 702 ppm Zn. Due to road construction since that sample was collected, it was difficult to locate the exact outcrop from which the earlier sample was obtained. The 2 dolomite marble samples collected from this area contained 59 and 19 ppm Zn, respectively.

## SUMMARY

Future work related to this project is dependent on the final analysis of ongoing whole-rock and mineral chemistry studies. Although only one potential target area for zinc oxide mineralization was located during this study (study area MA13), the project was successful in outlining several areas of clean calcite and dolomite marbles, and in discovering a new belt of Flinton Group rocks southwest of Renfrew.

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# 7. Project Unit 06-004. Newly Recognized Flinton Group Exposures Near the Renprior Zinc Occurrence, Northeastern Central Metasedimentary Belt, Grenville Province

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## INTRODUCTION

As part of the zinc scoping study (Easton, this volume, Article 6), work was conducted in the Ashdad–Remprior area in northern Mazinaw terrane (Storey and Vos 1981, study area MA4), near the Remprior (also known as Cadieux or Renfrew) zinc occurrence (Carter, Colvine and Meyn 1980). This mapping and sampling resulted in the discovery of a belt of Flinton Group rocks, preserved at upper amphibolite facies, in Admaston Township (Figure 7.1). This new-found belt is located approximately 22 km north-northwest of the previous northernmost Flinton Group exposure on Highway 511 at the Bagot–Blithfield townships boundary (Easton 1988). Furthermore, leucocratic silicate rocks associated with the zinc occurrence, previously mapped as felsic metavolcanic rocks, were probably derived from hydrated cherts, not volcanic rocks, as discussed in detail below. These observations indicate that the geological setting of this zinc occurrence is not well understood, and calls into question the volcanic-associated origin previously attributed to this zinc occurrence (Carter, Colvine and Meyn 1980; Sangster and Bourne 1982).

## RENPRIOR ZINC OCCURRENCE

The Remprior zinc occurrence (MDI31F07NE00063, UTM 366130E 5030240N) is hosted in dolomite, siliceous dolomite and calcite marble. Robertson (1984) provides a detailed description of the geology proximal to the occurrence. Mineralization, consisting mainly of sphalerite and pyrite, with minor galena, is stratabound and is commonly located near the contacts of the different marble types, with the siliceous dolomite marble being the most commonly mineralized unit. Based on work up until 1982, 4 zones of significant mineralization have been outlined, with an ore reserve calculation (not NI 43-101 compliant) of 280 000 metric tonnes of 9% Zn to an average depth of 130 m (Robertson 1984).

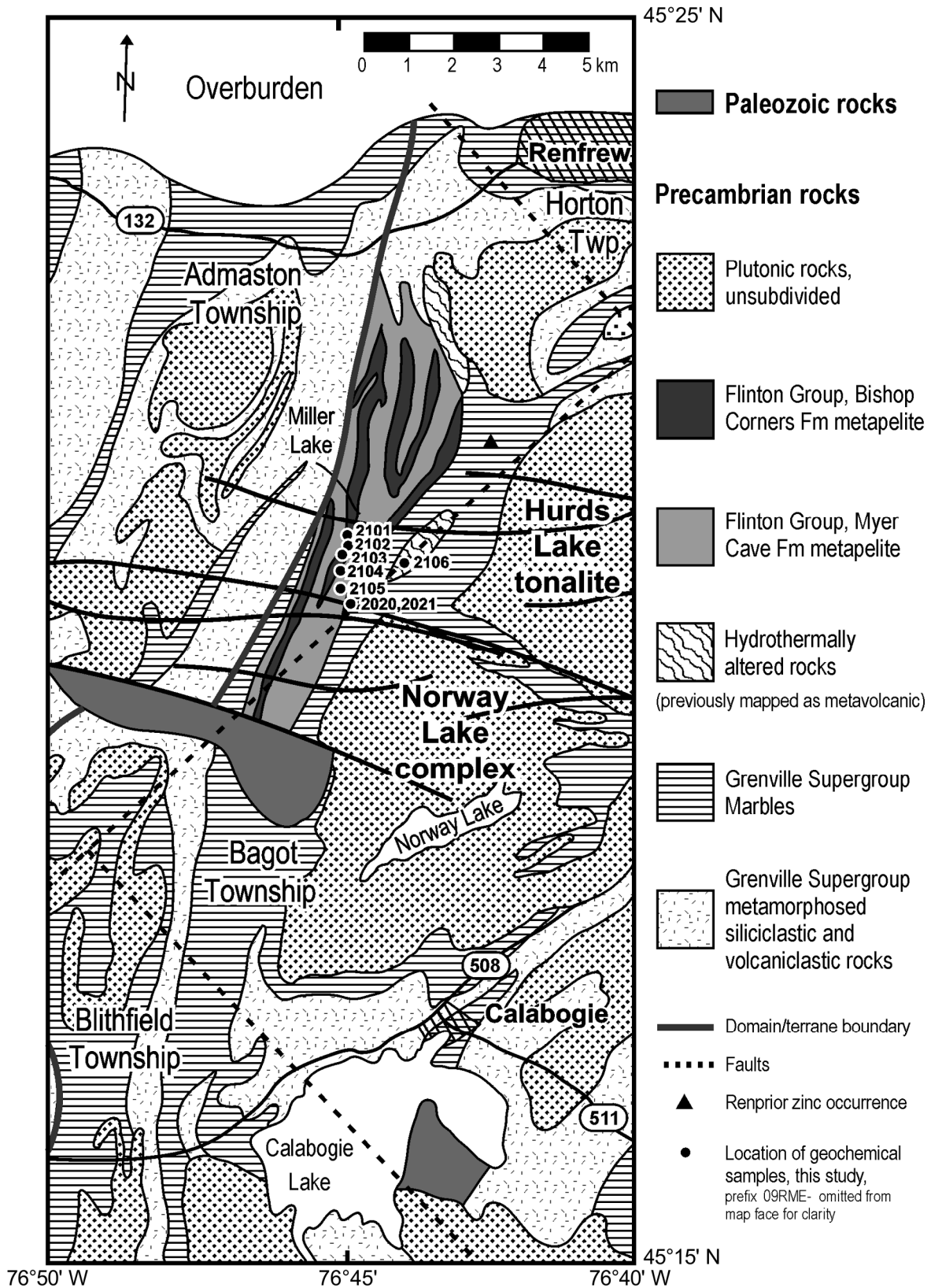
## THE FLINTON GROUP

The Flinton Group unconformably overlies rocks of the Grenville Supergroup (Moore and Thompson 1980), and was deposited after 1155 Ma, the age of the youngest detrital zircons present in metasediments of the Bishop Corners Formation (Sager-Kinsman and Parrish 1993). The Flinton Group was metamorphosed and deformed, along with the Grenville Supergroup rocks of Mazinaw terrane, at *circa* 1020 Ma (Corfu and Easton 1995). Rocks of the Flinton Group are apparently restricted in their distribution to Mazinaw terrane (Easton 1992).

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*Summary of Field Work and Other Activities 2009,  
Ontario Geological Survey, Open File Report 6240, p.7-1 to 7-7.*

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**Figure 7.1.** Simplified geological map of the regional setting for the Renprior zinc occurrence, showing the distribution of Flinton Group metapelitic rocks and compositionally unusual silicate gneisses.

Two distinct lithofacies packages are present in the Flinton Group: a conglomerate-sandstone lithofacies (Kaladar, Ompah and Norway Lake formations, Bishop Corners Formation) and a pelite-limestone-dolostone lithofacies (Bishop Corners, Myer Cave and Fernleigh formations) (Easton 2006). Rocks of the conglomerate-sandstone lithofacies are found mainly in the Northbrook area, whereas rocks of the pelite-limestone-dolostone lithofacies can be traced continuously as a linear belt, from Northbrook to the Flower Station. Metamorphic grade increases from greenschist facies in the Northbrook area to upper amphibolite facies in the Flower Station area (Easton 2006). Rocks of the new-found belt belong to the pelite-limestone-dolostone lithofacies.

## RESULTS

### Outcrop Observations

Figure 7.1 is a simplified geological map of the area around the Renprior zinc occurrence, which is located in southeastern Admaston Township. The Flinton Group rocks are well exposed on the K & P trail, north of Pucker Street to southwest of Miller Lake (*see* Figure 7.1). Metamorphic grade is upper amphibolite facies, at or near the breakdown reaction of muscovite to form sillimanite and potassium feldspar. Three main rock units are present, 2 of which contain abundant aluminous minerals and varied amounts of garnet, and 1 which is garnet rich. Contacts between the units were not observed. The mineralogy in the units suggests derivation from an aluminous mudstone parent, with the Flinton Group being the only regionally extensive aluminous mudstone unit in Mazinaw terrane. In addition, the narrow, linear geometry of these units is also typical of the higher grade portions of the Flinton Group. Finally, the high magnetic susceptibility of the sillimanite and micaceous gneisses (Table 7.1), likely due to the transformation of hematite to magnetite during upper amphibolite-facies metamorphism, is consistent with the mineralogy of the Flinton Group (Moore and Thompson 1980). In contrast, Grenville Supergroup units generally become less magnetic with increasing metamorphic grades (R.M. Easton, unpublished data).

From north to south along the K & P trail, the 3 units are

1. grey to dark grey rock, with large garnet crystals in an amphibole-rich matrix. This rock could be part of either the Ore Chimney or the Myer Cave formations, and is 50 to 75 m wide.
2. silvery-weathering, white mica-rich, locally migmatitic gneiss, 150 to 300 m thick. The high-mica content, and the presence in thin section of abundant tourmaline grains, is typical of Bishop Corners Formation mudstone at middle to upper amphibolite-facies metamorphism (Easton 2006).
3. grey, sillimanite gneiss, variably migmatitic, with either minor (<2%) or abundant (5 to 15%) garnet. Again, the mineralogy is typical of Myer Cave Formation mudstone at middle to upper amphibolite-facies metamorphism. This rock unit is 150 to 300 m wide.

Although Lumbers (1982) did not assign any of these rocks to the Flinton Group on his Renfrew map sheet, he did distinguish the mica-rich rocks that are likely correlative with the Bishop Corners Formation as a separate unit on his map; namely, “unit 7 - quartzose and feldspathic metasediments”. The only instance of this unit on his map was a series of 3 to 4 subparallel, northeast-trending linear belts located in southeast Admaston Township near Miller Lake. The unit 7 rocks of Lumbers (1982) are interlayered with an amphibole-rich metasedimentary rock unit (unit 8 of Lumbers 1982), which includes the Myer Cave Formation units, as well as Grenville Supergroup strata. The map pattern shown indicates tight isoclinal folding of the Flinton Group strata (Lumbers 1982).

**Table 7.1.** Geochemical data for Flinton Group samples from Admaston Township. Comparative samples 92RME-1032 and 94RME-0064, at similar metamorphic grade, are from Easton (2006). All analyses were performed at the OGS Geoscience Laboratories, Sudbury. UTM co-ordinates are NAD83, Zone 18.

Sample Number	09RME-2101	09RME-2102	92RME-1032	09RME-2103	09RME-2104	94RME-0064	09RME-2105	09RME-2106
<b>Easting</b>	362982	362986	359180	363032	363034	368010	362900	364298
<b>Northing</b>	5028163	5028172	4988010	5027743	5027684	4996045	5027268	5027860
<b>Rock Name</b>	Sillimanite gneiss	Garnet-sillimanite gneiss	Garnet-sillimanite gneiss	Micaceous gneiss	Micaceous gneiss	Micaceous gneiss	Garnet gneiss	Quartzose gneiss
<b>Formation</b>	Myer Cave	Myer Cave	Myer Cave	Bishop Corners	Bishop Corners	Bishop Corners	Myer Cave?	n/a
<b>Magnetic Susceptibility*</b>	53.0 2.63–160	12.1 0.43–16.1	n/a	12.1 7.1–68.3	51.0 17.4–103	n/a	1.16 0.2–1.95	0.04 0.03–0.06
SiO <sub>2</sub>	54.77	58.50	55.25	55.87	65.66	61.22	53.17	42.75
TiO <sub>2</sub>	1.14	1.23	1.33	1.43	1.11	1.06	1.57	0.06
Al <sub>2</sub> O <sub>3</sub>	17.93	19.29	19.70	20.32	15.21	15.11	21.12	7.48
Fe <sub>2</sub> O <sub>3</sub> <sup>total</sup>	16.26	10.89	16.05	11.26	7.97	10.05	14.37	0.37
MnO	0.04	0.08	0.04	0.02	0.07	0.06	0.11	0.01
MgO	1.69	2.17	1.67	0.82	2.18	2.01	1.92	0.38
CaO	0.48	0.39	0.47	0.28	0.37	0.33	0.50	0.89
Na <sub>2</sub> O	0.05	0.69	0.20	0.82	0.94	0.22	0.08	2.68
K <sub>2</sub> O	2.55	2.97	2.80	5.15	3.57	4.05	3.08	1.57
P <sub>2</sub> O <sub>5</sub>	0.33	0.06	0.21	0.12	0.15	0.20	0.18	0.04
CO <sub>2</sub>	<0.03	0.07	1.36	0.03	<0.03	<0.03	<0.03	0.61
LOI	4.39	4.16	<0.30	3.74	3.19	4.85	4.10	43.64
Total	99.61	100.44	99.08	99.84	100.42	99.16	100.20	99.85
Mg Number	17.1	28.3	17.1	12.6	35.1	28.4	20.9	67.1
CIA	85.3	82.6	85.0	76.5	75.7	85.3	85.2	59.3
Ba	305	337	725	521	510	179	592	394
Pb	10	23	<10	21	16	n/a	14	10
Li	196	206	n/a	53	67	n/a	130	83
Y	67	47	29	52	47	35	72	16
Zr	219	256	216	290	314	179	299	100
Total REE	253	230	102	245	196	108	358	142

**Notes:** \* Magnetic susceptibility values are  $\times 10^{-3}$  SI units: the first row is the average value for all readings at the sample site, the second row indicates range in values from lowest to highest.

Major element oxides are in weight percent, trace element data are in ppm;

Mg number = atomic Mg/Mg + Fe, where Fe = total Fe expressed as ferrous iron. Mg number and CIA are dimensionless.

**Abbreviations:** CIA = chemical index of alteration; LOI = loss-on-ignition; n/a = not applicable.

## Geochemistry

Samples 09RME-2101 and 09RME-2102 (*see* Table 7.1) were collected from garnet-rich and garnet-poor sillimanite gneisses exposed along the K & P trail immediately southwest of the tip of Miller Lake. Mineralogically, these rocks are consistent with upper amphibolite facies Myer Cave Formation exposures in the Ompah area (Easton 2006), as is their chemistry, notably the high alumina and iron contents, and the high chemical index of alteration (CIA) values. Samples 09RME-2103 and 09RME-2104 (*see* Table 7.1) were collected further south on the K & P trail, and are mica-rich metapelitic gneisses typical of the Bishop Corners Formation. Again, the geochemistry, both in terms of the alumina and potassium content, is consistent with this stratigraphic correlation. A fifth sample (09RME-2105, *see* Table 7.1) was garnet rich, and could be either part of the Myer Cave Formation, or it could be part of the Ore Chimney Formation, a paleosol locally developed at the base of the Flinton Group (Moore and Thompson 1980). As expected, all 5 Flinton Group samples exhibit rare earth element patterns similar to the post-Archean shale composite.

Sample 09RME-2106 was collected from a rock unit described by Lumbers (1982) as fine-grained quartzofeldspathic schist and gneiss possibly derived from felsic volcanic rocks. This unit appeared too homogenous and quartz rich to be derived from a felsic volcanic rock, and the geochemistry on this sample (09RME-2106) supports this observation, as the rock has low silica (42.75 weight %) and alumina contents (7.48 weight %) and an extremely high loss-on-ignition (LOI) value of 43.64 weight %. The low CO<sub>2</sub> and iron content of the rock indicates that mineralogical-bound water is the most likely reason for the high LOI of this rock. This rock has either undergone severe hydrothermal alteration, or was derived from a hydrated silica gel.

Flinton Group calcite marbles have trace element characteristics, most notably high strontium contents, distinct from Grenville Supergroup marbles (Easton 1995, 2006). Flinton Group dolomite marbles, however, are difficult to distinguish from Grenville Supergroup marbles geochemically (Easton 1995, 2006). All of the marble proximal to the Flinton Group metapelites on the K & P trail are tremolite-bearing dolomite marbles. As noted previously (Easton, this volume, Article 6), sample 09RME-2021, which was collected immediately south of the Flinton Group metapelitic rocks, exhibits a rare earth element pattern similar to the post-Archean shale composite and the adjacent Flinton Group metapelites. Thus, it is possible that this sample is a Flinton Group marble. Sample 09RME-2021 also contained 933 ppm Zn, 21 ppm Pb, and >4 ppm Cd. An adjacent sample from the same outcrop area (09RME-2020), although dolomitic, contains elevated Ba and Sr contents (>1740 ppm and 434 ppm, respectively), again suggestive that it may be related to the Flinton Group.

## TECTONIC AND METALLOGENIC CONSIDERATIONS

The observations from this study are preliminary, and are based on a limited amount of detailed mapping and sampling. Nonetheless, they indicate that our current understanding of zinc occurrences in the northeastern Central Metasedimentary Belt is incomplete and may, in part, be misleading.

The Flinton Group rocks are migmatitic, indicating that upper amphibolite-facies metamorphic conditions (minimum of 700°C, ~5 to 7 kilobars in the Darling area, 25 km to the south, Easton 2006) affected both the Flinton Group and previously metamorphosed Grenville Supergroup strata. The effects of multiple, high-grade metamorphism on the deposit has not been specifically addressed by previous workers, although Robertson (1984) did note the possibility of ore remobilization during deformation and metamorphism. Furthermore, the interpretation of lead-isotope data from Renprior occurrence galena grains (Fletcher and Farquhar 1977) needs to be re-evaluated, taking into account the effects of 2 high-grade metamorphic events.

The proximity of the Renprior zinc occurrence to the Flinton Group belt could be coincidental, or they may be genetically linked. For example, pre-metamorphic weathering and fluid movement related to the unconformity surface on which the Flinton Group was originally deposited may have been important in creating pore space in the dolomite and siliceous dolomite marbles that host the occurrence (depending on the timing of mineralization). If this were a significant process with respect to ore deposition, than other large areas of dolomite marble adjacent to the Flinton Group belt throughout Mazinaw terrane become highly prospective hosts for zinc mineralization.

The geochemistry of sample 09RME-2106 indicates that the volume of Grenville Supergroup metavolcanic rocks associated with the Renprior zinc occurrence is likely minor, and that some rocks previously considered to be volcanic in origin may be part of the metasedimentary package. The limited abundance of metavolcanic rocks near the occurrence is consistent with the regional distribution of metavolcanic rocks in Mazinaw terrane, which are found in large calc-alkalic volcanic centres, spaced roughly 40 km apart (Figure 7.2) (Easton 2006). Intervening areas are dominated by volcanoclastic

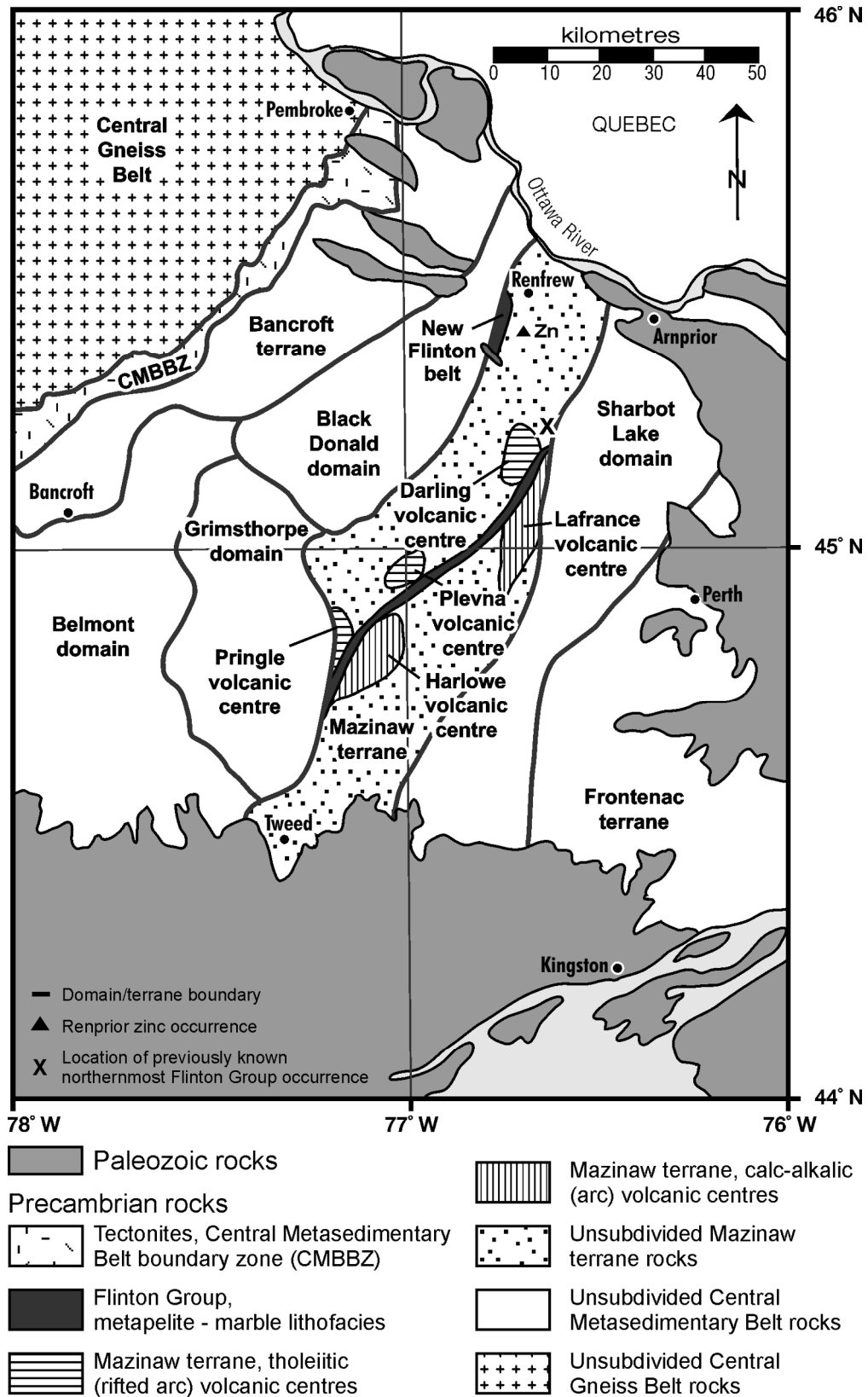


Figure 7.2. Distribution of major volcanic centres and sedimentary basins in Mazinaw terrane.

metasedimentary rocks, poorly sorted clastic metasedimentary rocks, and marbles. Calc-alkalic volcanic centres are located near Cloyne, and in the vicinity of Flower Station west and southwest of Calabogie Lake. The latter is located approximately 25 km southwest of the Renprior zinc occurrence (*see* Figure 7.2). Younger, bimodal metavolcanic rocks associated with Methuen intrusive suite monzogranite plutons occur in parts of Mazinaw terrane (Easton 2006), but neither intrusive nor extrusive rocks of this suite have been described from the Admaston area. Although the presence of distally deposited calc-alkalic metavolcanic rocks contemporaneous with formation of the host marbles at the Renprior zinc occurrence cannot be ruled out entirely, their influence is probably less significant than previous authors have suggested (e.g., Carter, Colvine and Meyn 1980; Sangster and Bourne 1982). Thus, the Renprior zinc occurrence may be more akin to other marble-hosted zinc occurrences in Ontario (e.g., Long Lake, 30 Island Lake, Salerno Lake, Spry) than previously thought.

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# 8. Project Unit 07-003. New Thorium Occurrence Near Tory Hill and Implications for Radioactive Mineral Exploration, Central Metasedimentary Belt, Grenville Province

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## INTRODUCTION

During the course of investigating potential field trip stops along Haliburton County Road 503 (formerly Highway 503) from Gooderham to Tory Hill, for use during the 2009 Friends of the Grenville field trip, the author discovered a granite roadcut that gave exceptionally high scintillometer readings, as summarized in Table 8.1. These readings triggered the high dose warning on the instrument, corresponding to an exposure rate at the point of contact of 2.2 to 4.1 mR/h (or 0.022 to 0.041 mSv/h). Exposure rate at 80 cm distance from the source was 0.60 mR/h (0.006 mSv/h). This is the first time the author has encountered outcrops in the field that triggered the high dose warning, even though the previous 2 years were spent documenting numerous radioactive occurrences in Cavendish Township. Only the length of the roadcut was examined, no survey of adjacent properties or soils was conducted.

**Table 8.1.** Assay mode scintillometer readings from the Haliburton County Road 503–Lee’s Road roadcut in Monmouth Township.

Rock Unit	Zone 17, NAD83		cps	K (wt %)	U (ppm)	Th (ppm)	Total (cpm)	K (cpm)	U (cpm)	Th (cpm)
	Easting (m)	Northing (m)								
Soil, surface	714270	4982560	28 400	21.1	181.6	2494.0	42 043	4371	4067	2190
Soil, 5 cm depth	714270	4982560	42 000	12.8	111.4	3148.7	49 047	4597	4761	2755
Rock	714271	4982565	27 500	8.6	328.0	2529.0	43 740	4690	4592	2217
Rock	714271	4982565	35 000	16.2	361.8	2342.1	43 534	4838	4436	2059
Monzogranite background	714259	4982536	275	4.8	7.5	22.2	1089	198	53	22
Cavendish high Th granites*	n/a	n/a	250 to 400	4.1	3.6	29.4	979	166	50	28

**Abbreviations:** cpm = counts per minute, cps = counts per second, n/a = not applicable, wt % = weight percent.

**Notes:** \*median of 64 readings of high-thorium granites from Cavendish Township (R.M. Easton, unpublished data, 2009).

Multiply K by 1.2046 for K<sub>2</sub>O, Th by 1.1379 for ThO<sub>2</sub>, U by 1.1793 for U<sub>3</sub>O<sub>8</sub>.

All K, U and Th data were recorded using an Exploranium™ GR-135G MiniSpec gamma-ray spectrometer, serial number 4885, calibrated on February 22, 2006, using an NaI crystal and software version 501GEO. The instrument was stabilized daily, and data were recorded using the assay mode with a 5-minute count time and automatic dead time correction. Dead time was approximately 70% for the soil and rock readings, typical dead time for average rocks is less than 10%. Quoted accuracy is 0.1% K, 0.4 ppm U, and 0.7 ppm Th for a sample with 2% K, 2 ppm U and 8 ppm Th.

*Summary of Field Work and Other Activities 2009,  
Ontario Geological Survey, Open File Report 6240, p.8-1 to 8-3.*

## SITE DETAILS

High readings were encountered at 2 locations on the roadcut, one in soil and one in rock (see Table 8.1), roughly 5 m apart (Photo 8.1). At the soil site, higher readings were encountered at depth (B to C horizon) (see Table 8.1), following collection of a sample of the soil (A and B horizon) for chemical analyses in order to confirm the scintillometer results. Sampling was conducted using a mask and disposable gloves, with subsequent wash down of all materials with water prior to disposal. These precautions were taken in order to prevent inhalation or ingestion of any radioactive particulates during or after sampling, and their use is recommended to anyone conducting subsequent sampling at this site.

The roadcut is located on the southeast corner of the junction of Haliburton County Road 503 and Lee's Road, and is adjacent to inhabited structures. The roadcut itself is nondescript, and is a medium-grained, pink-weathering, monzogranite. The less radiogenic portions of the outcrop have potassium, uranium and thorium contents similar to late granites (*circa* 1065 Ma) of the high-thorium granite suite (see Table 8.1), which is present within Cavendish Township to the south, as well as elsewhere in the Central Metasedimentary Belt (Easton 2008).

There are no previously known radioactive occurrences or old exploration pits within 750 m of this roadcut. This is not surprising, given that most exploration in the area has targeted either granite pegmatite or marble skarn as host rocks for uranium mineralization, not granite. There is no airborne gamma-ray anomaly associated with this site, but it does lie immediately south of a large regional airborne thorium and uranium anomaly (Carson et al. 2004a, 2004b, 2004c).



**Photo 8.1.** Roadcut on Haliburton County Road 503, view southeast, showing relative location of high radioactive soil site (right, by hammer handle) and high radioactive rock site (left, by scintillometer). Clipboard is on the shoulder of the road.

## IMPLICATIONS FOR EXPLORATION

Although mineralization is extremely localized, this occurrence is significant as it indicates that even small granite bodies of the high-thorium granite suite can contain significant enrichment in radioactive elements—in this case, thorium. This confirms the potential for granite-related (Rössing-style) uranium mineralization in the Central Metasedimentary Belt, as outlined in detail in Easton (2008).

This occurrence also indicates that there is the potential to find new occurrences in the Central Metasedimentary Belt in areas near major airborne anomalies and even where there has been considerable past exploration.

Finally, this occurrence adds to our understanding of the distribution of radioactive elements in major rock units of southern Ontario.

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# 9. Project Unit 07-003. Characterization of Rock Units in the Grenville and Southern Provinces by *In-Situ* Geophysical Measurements and Geochemistry

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## INTRODUCTION AND PREVIOUS WORK

Banman and Easton (2008) reported preliminary results from a project to document the methodology and accuracy of using a hand-held scintillometer and a magnetic susceptibility meter for the discrimination of intermediate to felsic intrusive rocks in the Grenville Province. This article summarizes the results of that project, as well as briefly reporting on the use of the same methodology on mafic to intermediate metavolcanic rocks and metasandstone from the Southern Province near Elliot Lake.

Previous research on the topic is limited. King (1997) collected thousands of magnetic susceptibility measurements in the sedimentary Meguma Group, central Nova Scotia, in order to assist in interpreting aeromagnetic data from the area. King (1997) found a strong correlation between general magnetic character and stratigraphy down to the member level. He was also able to differentiate between slate, metamorphosed sandstone, silty slate, and sulphide-rich sand beds (King 1997). Beakhouse (2000) documented the use of magnetic susceptibility measurements to discriminate between plutonic suites and metavolcanic units in the Wabigoon Subprovince of the Superior Province in northwestern Ontario.

Lundin and Bastani (2007) collected specific gravity, magnetic susceptibility, geochemistry, and ground gravity seismic data from 2 granitoid suites in the Svecofennian Province of Sweden. They found that the *in-situ* data correlated well with airborne and gravity data. In addition, they found a linear relationship between uranium and thorium concentrations, and that potassium and uranium did not correlate well in the felsic rocks. Lundin and Bastani (2007), however, did not collect whole-rock geochemistry samples at any of the sites of their *in-situ* gamma ray spectrometer measurements; thus, the accuracy of their ground gamma-ray data cannot be determined.

## INTRUSIVE ROCKS, CAVENDISH TOWNSHIP, GRENVILLE PROVINCE

### Methodology

The detailed study by Banman (2009) study focussed on 4 outcrop areas from 4 separate intrusions exposed along Peterborough County Road 507 in Cavendish Township, within the Central Metasedimentary Belt of the Grenville Province (Easton 2007, 2008). The sites were chosen because of accessibility and an abundance of fresh outcrop for both geochemical sampling and the collection of measurements. A fifth site, located on the Galway Township Forest Access Road, is unique, as it contains a granodiorite gneiss that has undergone intense weathering. It was selected specifically to examine the influence of extreme weathering on bulk rock composition.

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*Summary of Field Work and Other Activities 2009,*  
Ontario Geological Survey, Open File Report 6240, p.9-1 to 9-4.

**Table 9.1.** Summary of magnetic susceptibility and scintillometer measurements from granitic rocks in Cavendish Township.

Site	Intrusive Unit and Age	Rock Type	UTM Location (NAD83, Zone 17)	Average Specific Gravity	Average Scintillometer Data			Average Magnetic Susceptibility ( $\times 10^{-3}$ SI)
					K (wt %)	U (ppm)	Th (ppm)	
1	Catchacoma (high Th) Suite, 1067 $\pm$ 4 Ma	syenogranite	710700E 4954000N	2.64	4.0	3.5	28.3	10.6 (max 15.5)
2	Quartz Monzodiorite Suite emplacement age unknown	quartz monzodiorite gneiss	710670E 4954400N	2.73	2.7	1.2	0.6	14.8 (max 39.8)
3	Methuen Suite, Junction pluton 1221 $\pm$ 2 Ma	gneissic monzogranite	707425E 4969475N	2.66	2.9	4.1	9.1	3.6 (max 10.0)
4	Methuen Suite, Galloway pluton ~1220–1240 Ma	gneissic granodiorite to monzogranite	708000E 4964600N	2.68	2.8	4.2	6.1	0.1 (max 0.22)
5a	Elzevir Suite, ~1270–1290 Ma	granodiorite gneiss	704640E 4953250N	n/a	4.5	7.3	7.9	81.4
5b	age unknown	saprolite	704640E 4953250N	n/a	3.6	5.5	8.0	49.8

**Abbreviations:** cpm = counts per minute, cps = counts per second, n/a = not applicable, wt % = weight percent.

**Notes:** Multiply K by 1.2046 for K<sub>2</sub>O, Th by 1.1379 for ThO<sub>2</sub>, U by 1.1793 for U<sub>3</sub>O<sub>8</sub>.

All K, U and Th data were recorded using an Exploranium™ GR-135G MiniSpec gamma-ray spectrometer, serial number 4885, calibrated on February 22, 2006, using an NaI crystal and software version 501GEO. The instrument was stabilized daily, and data were recorded using the assay mode with a 5-minute count time and automatic dead time correction. Quoted accuracy is 0.1% K, 0.4 ppm U, and 0.7 ppm Th for a sample with 2% K, 2 ppm U and 8 ppm Th.

Magnetic susceptibility data were recorded using an Exploranium™ KT-9 Kappameter, serial number 5890.

Geochronology data from Easton and Kamo (2008, 2009).

**Table 9.2.** Comparison of geochemical and scintillometer data for granitic rocks in Cavendish Township (from Banman 2009).

Site	Rock Type	Average Geochemistry Values			Average Scintillometer Data		
		K (wt %)	U (ppm)	Th (ppm)	K (wt %)	U (ppm)	Th (ppm)
1	Syenogranite	4.7	4.4	42.5	4.0	3.5	28.3
2	Quartz monzodiorite gneiss	3.2	1.7	3.2	2.7	1.2	0.6
3	Gneissic monzogranite	3.2	3.9	14.7	2.9	4.1	9.1
4	Gneissic granodiorite to monzogranite	2.3	4.1	7.9	2.8	4.2	6.1
5a	Granodiorite gneiss	4.1	4.5	9.7	4.5	7.3	7.9
5b	Saprolite	3.6	4.1	11.6	3.6	5.5	8.0

**Abbreviations:** n/a = not applicable, ppm = parts per million, wt % = weight percent.

The 4 primary sites were chosen because they had unique combinations of physical and chemical properties: magnetic susceptibility, radiometric signature, level of homogeneity, and degree of metamorphism and deformation (Table 9.1). This provided a spectrum of properties that could be examined as to how each might influence the geophysical measurements taken during a typical mapping program. Each site, except site 5, was a roadcut, roughly 75 to 100 m in length, within an individual intrusion. Each site was divided into 4 stations: 2 located near each end of the outcrop, with the other 2 more centrally located, so that each station divided the outcrop area evenly (10 to 15 m apart). In essence, each station represents a small outcrop, whereas each site represents a large outcrop area, similar in scale to the largest outcrops typically encountered during mapping.

At each station, 4 to 7 sets of magnetic susceptibility measurements (each set contains 10 readings) and 4 to 7 scintillometer readings were taken within a 1 to 2 m<sup>2</sup> area. A sample was collected, from under one of the scintillometer measurement locations at each station, for thin section, whole-rock geochemistry, and specific gravity determination in order to link the geophysical data directly with the petrography of the sample. A total of 74 sets of magnetic susceptibility readings, 74 assay-mode scintillometer measurements, and 17 rock samples were collected. Results are summarized in Tables 9.1 and 9.2.

## Results

All 5 sites exhibit differences in magnetic susceptibility, and potassium, thorium and uranium contents as determined by the scintillometer and by geochemistry. The Galloway and Junction plutons differ notably in magnetic susceptibility and thorium content, even though they are of similar age and geochemical affinity. Thorium is higher in the Junction pluton, in part reflecting the overall monzogranitic composition of that more homogeneous intrusion. The Junction pluton is also wider (3 km across) and the sample site was located near the core of the intrusion. Thus, the higher magnetic susceptibility recorded from the Junction pluton may reflect a lower degree of metamorphic recrystallization during regional metamorphism and deformation, than in the narrower (<1 km) and more compositionally heterogeneous Galloway pluton.

Statistical analysis by Banman (2009) found that there was no significant difference between the geochemical and the scintillometer measurements for potassium or uranium. This result is not surprising, as the scintillometer collects data from a volume of rock, roughly similar in volume to a large hand sample. There was a significant difference for thorium, however, with the scintillometer measurements being consistently lower than the geochemical results by 30 to 40% (*see* Table 9.2). This was the case even for samples with higher thorium abundances (>20 ppm). The most likely explanation for the difference between the 2 methods is that there is a calibration problem with the software program that the instrument uses to calculate thorium content. Nevertheless, the relative abundance of thorium in outcrop was measured consistently by the scintillometer, so that it was still possible to recognize differences in thorium content between all 5 sample sites (*see* Table 9.1) even though the scintillometer-determined thorium content was not wholly accurate.

Although not specifically addressed by Banman (2009), the data collected in the study indicate that 2 to 3 assay-mode scintillometer measurements are sufficient to characterize a relatively homogeneous geological unit. As each measurement takes 5 minutes, excluding dead time, the fewer the measurements needed, the better. In terms of characterizing intrusive suites, the advantage of the scintillometer is that it provides real-time data to the geologist, as well as allowing them to collect data from a greater number of outcrops than would be possible utilizing only geochemical samples.

## APPLICATION TO METASEDIMENTARY, MAFIC INTRUSIVE AND METAVOLCANIC ROCKS, ELLIOT LAKE, SOUTHERN PROVINCE

Use of the scintillometer to characterize rock units is not restricted to intermediate to felsic intrusive rocks. During the 2009 mapping season in the Elliot Lake area (*see* Easton, this volume, Article 10), the scintillometer was used to map out a chemical stratigraphy within metasedimentary rocks of the Matinenda Formation of the Huronian Supergroup (*see* Easton, this volume, Table 10.4), to discriminate between Archean and Paleoproterozoic metavolcanic rocks (*see* Easton, this volume, Table 10.1) and to map out feeder dikes to metamorphosed basaltic andesite flows within the Huronian Supergroup (*see* Easton, this volume, Table 10.1). As documented in greater detail (*see* Easton, this volume, Article 10), the ability to map out changes in potassium, thorium and uranium content with stratigraphic height in the

Matinenda Formation is likely due to the variations within clay, monazite and zircon content within this particular formation. Also, as documented (*see* Easton, this volume, Article 10), small differences in potassium (<0.5 weight %) and thorium content (<5 ppm) could be recorded consistently, and could be used to distinguish between Archean and Paleoproterozoic mafic metavolcanic rocks. Thus, for certain types of mapping projects, the scintillometer can augment field observations with data that cannot be obtained easily by other means.

## CONCLUSIONS

- Use of the scintillometer, in conjunction with whole-rock geochemistry, is a cost-efficient way to map plutonic, metasedimentary and mafic metavolcanic rocks within the Canadian Shield.
- Although certain instruments underestimate thorium contents (low accuracy), precision is sufficient to allow discrimination of rock units on the basis of relative compositional differences between rock units.
- The scintillometer is a more consistent discrimination tool than the magnetic susceptibility meter, as some rock units show considerable variability in their magnetic character depending on their metamorphic and deformation history. That being said, use of both instruments together is better than using only one or the other.

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# 10. Project Unit 09-004. Compilation Mapping, Pecors–Whiskey Lake Area, Southern and Superior Provinces

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## INTRODUCTION

The Pecors–Whiskey Lake map area (Figure 10.1) covers approximately 400 km<sup>2</sup>; and includes all or part of Deagle, Esten, Gaiashk, Gunterman, Joubin and Proctor townships (formerly townships 136, 137, 142, 143, 148 and 149). Approximately 8 weeks of the 2009 field season were spent mapping in the area.

The area was selected for mapping because of renewed uranium exploration in the Elliot Lake area, using either the traditional placer model or an Athabaskan-basin unconformity and basement fracture model. Published mapping of Proterozoic rocks in the Elliot Lake area, however, dates mainly from the late 1950s and the early 1960s (Robertson 1961, 1962, 1968, 1970, 1977), prior to the establishment of formalized Huronian Supergroup stratigraphy and the recognition of units such as the Livingstone Creek Formation. Although mapping of the Archean basement rocks in the Whiskey Lake greenstone belt was done in the early 1990s, the maps were released as unedited, black and white preliminary or open file maps (Jensen 1992; Rogers 1991). Consequently, there is a need for a new, detailed (1:20 000 scale), geological map for the southern part of the Quirke Lake syncline, focussing on improved mapping of the Archean–Proterozoic unconformity as well as upgrading the mapping in key areas. In addition, although an extensive geochemical database exists for the Whiskey Lake greenstone belt (e.g., Byron, Whitehead and Davies 1994; Easton and Sykora 2007), little geochemical data exist for the Huronian Supergroup metavolcanic rocks in the Elliot Lake area.

Additional problems to be addressed during the mapping program included the following:

1. There is a need to be able to distinguish between Nipissing gabbro and East Bull Lake intrusive suite gabbros in the map area and to geochemically characterize all the different gabbroic units in the area in order to ascertain their mineral potential.
2. Previous workers in the area have reported difficulty differentiating Huronian Supergroup versus Archean metavolcanic rocks in both outcrop and in core. Mapping and sampling should focus on establishing field criteria to assist in discriminating between the 2 rock types.
3. The Archean–Proterozoic unconformity should be better located, especially in areas where Huronian Supergroup and Archean metavolcanic rocks are in contact. In addition, the unconformity should be mapped and sampled with the intent to determine if there are features indicating that uranium has moved “hydrothermally”.
4. Livingstone Creek Formation strata present on the southwest side of Pecors Lake should be mapped out, and identified and mapped where it may be found elsewhere in the map area.
5. Many gold showings are geochemical anomalies (highs) located in sulphide iron formation, with assay values difficult to verify from the literature. These showings need to be examined and assay values documented.

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*Summary of Field Work and Other Activities 2009,  
Ontario Geological Survey, Open File Report 6240, p.10-1 to 10-21.*

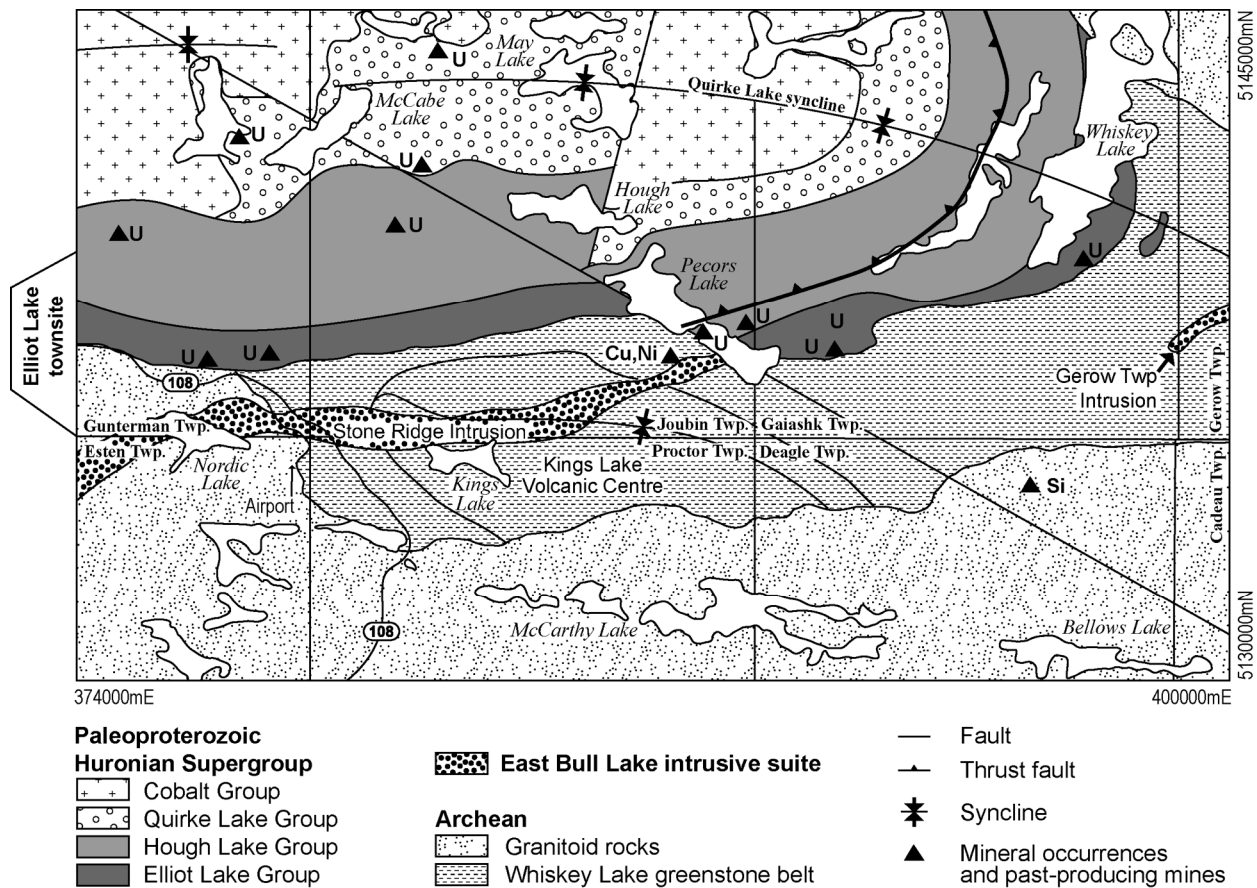
© Queen's Printer for Ontario, 2009

6. East of Pecors Lake in Gaiashk Township, felsite dikes have been reported in Terex drill core. The felsite dikes were associated with albitic(?) alteration halos and brecciation, and one generation of dike contained up to 1.8 pounds per ton  $U_3O_8$  (~842 ppm U), which is as high as the radioactive conglomerates. Robertson (1961, 1962, 1968) noted that these dikes are closely associated with Nipissing gabbro intrusions, and might be related to them. Are these dikes picking up uranium from the conglomerates or are they bringing uranium into the system? A geochemical and geochronological study on these dikes is being conducted by researchers from Michigan State University (Finlayson and Rooney 2009).
7. Are the 'paleosols' at Elliot Lake true paleosols, or are they the result of alteration along the more permeable unconformity, or both? Mapping should be conducted with this question in mind.

## GEOLOGICAL SETTING

### Whiskey Lake Greenstone Belt

The southern half of the study area is underlain by the Whiskey Lake greenstone belt, a 40 km long by 10 km wide, metamorphosed Archean greenstone belt, located about 25 km east-southeast of Elliot Lake. The Whiskey Lake greenstone belt is bounded to the west, south and east by Archean granitoid



**Figure 10.1.** Simplified geological map of the Pecors–Whiskey Lake map area. For clarity, Nipissing gabbro intrusions and many faults are not shown. Abbreviations: Cu, copper; Ni, nickel; U, uranium. Note: uranium occurrences include subsurface occurrences defined by diamond drilling. The Universal Transverse Mercator (UTM) co-ordinates are provided using North American Datum 1983 (NAD83) in Zone 17.

rocks. To the north, the belt is unconformably overlain by metamorphosed Paleoproterozoic supracrustal rocks of the Huronian Supergroup present within the Quirke Lake syncline (*see* Figure 10.1).

The Archean supracrustal rocks comprise metamorphosed komatiitic, tholeiitic and calc-alkalic volcanic rocks, and interflow metasedimentary rocks, cut by metamorphosed subvolcanic calc-alkalic porphyritic dikes, sills and stocks. The supracrustal stratigraphy is dominated by a calc-alkalic volcanic pile centred on Kings Lake, which formed on a platform of tholeiitic and komatiitic basalts (Jensen 1994). The Kings Lake calc-alkalic volcanic pile consists of mafic to felsic volcanic flows and proximal pyroclastic rocks, including FII and FIII rhyolites (Byron, Whitehead and Davies 1994) intruded by mafic to felsic subvolcanic dikes, sills and stocks. Marginal to the Kings Lake volcanic pile are metamorphosed iron formation, chert, wacke and mudstone deposited with distal pyroclastic units that interfinger with the uppermost tholeiitic and komatiitic flows. In the core of the Kings Lake volcanic pile are zones of hydrothermal alteration resulting from emplacement of the subvolcanic rocks (Jensen 1994). Rocks of the mafic platform are best exposed southeast of Whiskey Lake. Currently, no U/Pb geochronological data are available from any of the volcanic or intrusive units in the Whiskey Lake greenstone belt.

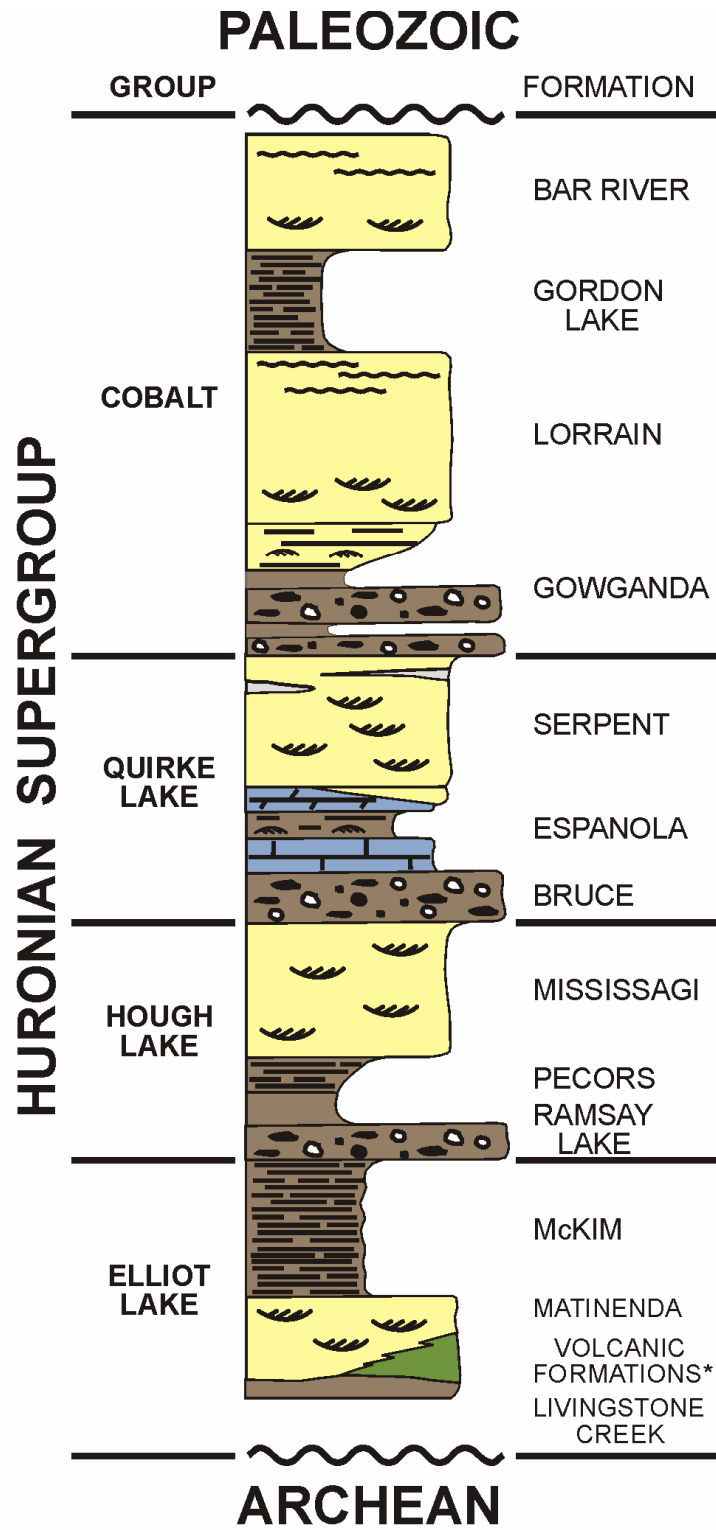
Metamorphic grade of the supracrustal rocks range from amphibolite facies near Depot Lake to lower greenschist facies near Whiskey Lake. All of the layered rocks dip north to northeast, and have been folded about a syncline, centred on the Kings Lake volcanic pile, that has a north-northeast-trending axis (Jensen 1994).

## Quirke Lake Syncline

Paleoproterozoic sedimentary and volcanic rocks of the Huronian Supergroup, metamorphosed to lower greenschist facies, constitute the northern half of the area, and are located along the southern limb of the east-trending Quirke Lake syncline (*see* Figure 10.1). All Huronian Supergroup units, up to the Lorrain Formation (Figure 10.2), are found in the Elliot Lake area. Rocks of the Huronian Supergroup are intruded by sills and dikes of Nipissing gabbro (2220 to 2210 Ma). In places, Livingstone Creek Formation metaconglomerate and breccia, metamorphosed Thessalon Formation metamorphosed iron-rich tholeiitic basalts and basaltic andesites, and metamorphosed conglomerate and feldspathic sandstones of the Matinenda Formation unconformably overlie the Archean supracrustal and granitoid rocks. Easton (2006) noted that rocks of the Huronian Supergroup had undergone at least 2 phases of folding. There is evidence for similar polyphase folding in the Quirke Lake syncline in the vicinity of May Lake, where the contact between the Espanola and Serpent formation has been repeated due to an interference fold pattern resulting from the intersection of the main, easterly Quirke Lake trend and secondary(?), north-northwest-trending folds. Economic uranium mineralization within the Elliot Lake area is confined to pyrite-bearing, quartz pebble conglomerate horizons, deposited within ancient fluvial channels in the Ryan and Manfred members of the Matinenda Formation (e.g., Pienaar 1963; Roscoe 1969; Robertson 1976, 1986).

## RESULTS

The mapping results in this study are augmented by 20 preliminary geochemical analyses, 60 thin sections, more than 800 scintillometer assay mode stations recording potassium, uranium and thorium, and more than 800 magnetic susceptibility measurements. As detailed below, in addition to characterizing uranium mineralization within the area, the scintillometer was an invaluable field mapping tool for discriminating between Archean and Paleoproterozoic mafic intrusive and extrusive rock, as well as in stratigraphic correlation of sandstone units. Results are discussed in order of decreasing stratigraphic age and address many of the geoscience problems outlined in the introduction to this article.



\*Thessalon, "Dollyberry Volcanics", Salmay Lake, Elsie Mountain, Stobie, Copper Cliff

Figure 10.2. Generalized stratigraphic column for the Huronian Supergroup (from Jackson 2001).

**Table 10.1.** Median scintillometer assay mode readings for the major rock units within the map area.

Rock Unit	n	K (wt %)	U (ppm)	Th (ppm)	Total (cpm)	K (cpm)	U (cpm)	Th (cpm)
Archean tholeiitic mafic metavolcanic rock	10	0	0	0	100	0	0	0
Archean calc-alkalic mafic metavolcanic rocks	19	0.6	0	1.6	186	19	1	2
Archean intermediate metavolcanic rocks	25	0.9	0	1.4	217	28	2	2
Thessalon Fm mafic metavolcanic rocks	32	0.8	0.9	4.5	293	33	7	5
Thessalon Fm intermediate metavolcanic rocks	22	3.2	2.0	6.1	466	87	17	8
vesicular dikes (feeders to Thessalon intermediate metavolcanic rocks)	10	2.8	2.7	7.0	547	103	16	8
Archean metagabbro	20	0	0	0	95	0	0	0
Matachewan dikes	16	0.5	0.0	1.4	191	18	2	2
Nipissing metagabbro	16	0.8	0.0	2.3	210	23	2	3
Stone Ridge metanorite – all	47	0.2	0.0	0.9	132	6	0	1
Stone Ridge metanorite – orthopyroxene preserved	30	0.1	0.0	0.5	122	11	0	1
Stone Ridge metanorite – recrystallized	17	0.4	0.0	1.4	164	11	0	1
Dike cutting Nipissing metagabbro	3	0.7	0.0	3.0	196	20	0	3
Lamprophyre dike (Table 10.2: 09RME-0074)	2	6.4	3.9	0.8	812	204	11	4

**Abbreviation:** cpm = counts per minute, n = number of samples, ppm = parts per million, wt. % = weight percent.

**Notes:** multiply K by 1.2046 for  $K_2O$ , multiply U by 1.1793 for  $U_3O_8$ .

All K, U and Th data were recorded using an Exploranium™ GR-135G MiniSpec gamma-ray spectrometer, serial number 4885, calibrated on February 22, 2006, using an NaI crystal and software version 501GEO. The instrument was stabilized daily, and data were recorded using the assay mode with a 5-minute count time. Quoted accuracy is 0.1% K, 0.4 ppm U, and 0.7 ppm Th for a sample with 2% K, 2 ppm U and 8 ppm Th.

## Newly Recognized East Bull Lake Intrusive Suite Intrusions in the Whiskey Lake Greenstone Belt

### STONE RIDGE INTRUSION

An east-trending metagabbro intrusion, 700 to 1000 m wide, with a minimum strike length of 15 km, lies 1 to 2 km south of, and roughly parallels, the Archean–Proterozoic unconformity in the southern part of the map area. Historically, this intrusion has been mapped as a Nipissing intrusive suite metagabbro; however, field and geochemical observations suggest that this assignment is incorrect, and that the intrusion is Paleoproterozoic in age. It is proposed herein that this intrusion be formally named the Stone Ridge Intrusion. The name is derived from the Stone Ridge golf course, where the intrusion is well exposed, and which is also adjacent to the principal reference section for the intrusion along Highway 108. Secondary reference sections are present in an abandoned gravel pit on Scott Road (UTM 374200E 5134871N, NAD83, Zone 17) and along the snowmobile trail that links the Elliot Lake airport and the Algom–Nordic Road.

Large parts of the intrusion contain preserved primary mineralogy. The predominant rock type is a weakly metamorphosed, grey to light grey weathering, medium-grained, leuconorite to leucogabbronorite (mafic mineralogy is dominated by orthopyroxene, in the range from 65 to 50%). Where recrystallized, mafic mineralogy is altered to amphibole, and the rock takes on a greener colour. Scintillometer measurements (Table 10.1) indicate a slight increase in potassium content in the recrystallized parts of the intrusion. Texturally, the body is remarkably uniform, but coarser grained to pegmatitic patches of gabbro occur along the northern margin of the intrusion, and are well exposed on Highway 108. Cryptic

igneous layering, consisting of plagioclase-rich and normal leuconorite can be observed in clean exposures present in the abandoned gravel pit on Scott Road (Photo 10.1). It is possible that this style of layering is present though large portions of the intrusion, but is obscured due to less than ideal exposures.

The age of the intrusion is constrained to less than *circa* 2650 Ma, the age of the youngest known granitoid rocks in the Ramsey–Algoma gneiss terrane, but older than *circa* 2473 Ma, the age of classic, plagioclase-phyric Matachewan dikes which were observed to intrude the body (e.g., at UTM 381576E 5135644N, NAD83, Zone 17). The latter observation precludes the Stone Ridge Intrusion being part of the Nipissing intrusive suite, as that suite was not emplaced until 2220 to 2210 Ma.

Existing and new geochemical data also suggest that the Stone Ridge Intrusion may not be part of the Nipissing intrusive suite, although it can sometimes be difficult to distinguish high-magnesium Nipissing gabbros from some members of the Paleoproterozoic East Bull Lake intrusive suite (Easton and James 1997; Easton and Murphy 2002). Available data from Jensen (1994) and Jobin-Bevans and Lyon (2001) from the Stone Ridge Intrusion, which both considered to be a Nipissing gabbro, are more suggestive of an East Bull Lake intrusive suite affinity. This interpretation is based on the low SiO<sub>2</sub> and TiO<sub>2</sub> and moderate Al<sub>2</sub>O<sub>3</sub> contents of the rocks, as well as their low thorium, uranium, yttrium, zinc and zirconium contents (Table 10.2: sample 09RME-0102), and flat rare earth element pattern with a very slight negative cerium anomaly and no europium anomaly. They also stand out from typical Nipissing gabbros in their scintillometer signature, being characterized by low potassium, uranium and thorium contents, approximately half of that found in Nipissing gabbros (*see* Table 10.1).

Although related to the East Bull intrusive suite, the Stone Ridge Intrusion is not a thick, layered mafic intrusion akin to the East Bull Lake, Agnew and River Valley intrusions. Rather, it is a linear body of relatively massive, medium-grained metagabbro to metanorite that may represent part of the feeder system to the larger East Bull Lake intrusive complexes, or to the Matachewan dike swarm. It is more



**Photo 10.1.** Subhorizontal igneous layering in the Stone Ridge Intrusion. Hammer handle is 33 cm long. Location: UTM 374201E 5134871N, NAD83, Zone 17.

akin to an intrusive body exposed in a roadcut on Highway 533 approximately 5.5 km south of the East Bull Lake intrusion (Stop 1 in Easton, Jobin-Bevans and James 2004).

The margins of the layered East Bull Lake intrusions are known to be favourable exploration targets for contact-style nickel-copper-platinum group element (PGE) mineralization (e.g., James et al. 2002). The mineral potential of these more homogeneous, linear bodies, such as the Stone Ridge Intrusion, is as yet unknown.

**Table 10.2.** Geochemical data for samples from the Pecors–Whiskey Lake area. All analyses were performed at the OGS Geoscience Laboratories, Sudbury. UTM co-ordinates are NAD83, Zone 17.

Sample Number	09RME-0042	09RME-0073	09RME-0055	09RME-0056	09RME-0034	09RME-0029	09RME-0102	09RME-0074
<b>Easting</b>	385173	381018	380118	380132	384826	385565	379171	381013
<b>Northing</b>	5138008	5132484	5130061	5130065	5137826	5137778	5135879	5132567
<b>Rock Name</b>	Basaltic andesite vesicular flow	Basaltic andesite vesicular dike	Gabbro dike	Plagioclase-phyric gabbro dike	Pillowed metabasalt	Gabbro dike	Leuconorite	Lamprophyre dike
<b>Unit</b>	Thessalon Formation	Thessalon Formation	Matachewan dike swarm	Matachewan dike swarm	Thessalon Formation	East-trending dike	Stone Ridge Intrusion	n/a
SiO <sub>2</sub>	54.26	51.74	52.41	50.47	55.59	49.79	52.16	47.46
TiO <sub>2</sub>	1.84	2.73	1.37	1.13	1.52	0.89	0.44	1.38
Al <sub>2</sub> O <sub>3</sub>	14.47	13.27	13.12	14.26	11.95	14.00	15.74	14.42
Fe <sub>2</sub> O <sub>3</sub> <sup>total</sup>	15.56	15.88	15.87	14.27	15.14	14.67	9.2	16.27
MnO	0.13	0.19	0.23	0.21	0.15	0.26	0.17	0.24
MgO	1.96	3.83	4.70	5.85	0.93	6.82	9.76	8.43
CaO	1.61	7.15	8.17	10.09	4.75	7.55	12.46	3.07
Na <sub>2</sub> O	<0.01	2.72	3.28	1.81	3.38	2.83	1.62	<0.01
K <sub>2</sub> O	6.43	1.66	1.14	0.87	1.16	0.05	0.31	6.48
P <sub>2</sub> O <sub>5</sub>	0.36	0.56	0.18	0.12	0.24	0.10	0.04	0.17
CO <sub>2</sub>	0.94	0.12	<0.03	<0.03	3.46	0.72	0.08	0.03
LOI	2.71	0.88	0.96	1.90	5.48	3.91	0.35	1.83
Total	99.43	100.61	101.43	101.00	100.40	100.88	101.25	99.72
Mg Number	19.9	32.3	37.0	44.8	10.9	47.9	65.4	50.7
CIA	67.1	53.8	51.0	52.7	67.2	59.0	52.4	60.3
Cr	16	54	42	143	7	86	114	67
Co	55	47	51	52	30	60	49	53
Cu	247	43	126	159	32	121	146	154
Ni	123	31	42	74	12	89	151	48
Pb	5	12	5	6	3	5	5	4
Zn	87	157	137	113	66	134	67	203
Ba	931	663	293	187	217	22	72	1121
Rb	168	60	70	52	39	1	10	287
Sr	20	319	231	199	31	348	123	177
Th	9.0	6.6	2.9	2.0	4.9	1.4	1	2.2
U	2.2	1.3	0.7	0.5	1.0	0.3	0.3	1.3
Hf	6.7	7.9	3.6	2.7	4.7	1.9	0.9	3.4
Nb	26.8	36.6	6.6	5.1	7.0	2.5	1.4	5.9
Y	27	35	35	29	33	20	12	35
Zr	271	323	138	101	177	70	35	128
Total REE	210	287	108	75	77	57	28	82

**Notes:** Major element oxides are in weight percent, trace element data are in ppm; Mg number = atomic Mg/Mg + Fe, where Fe = total Fe expressed as ferrous iron. Mg number and CIA are dimensionless.

**Abbreviations:** CIA = chemical index of alteration, LOI = loss-on-ignition, n/a = not applicable.

## GEROW TOWNSHIP LAYERED INTRUSION

An east-trending metagabbro intrusion, 100 to 300 m wide, with a minimum strike length of 300 m, straddles the Gaiashk–Gerow townships boundary immediately north of the main hydro transmission line that cuts through these townships. The intrusion lies roughly 4 km southwest of the western part of the Paleoproterozoic East Bull Lake intrusion. The Gerow Township intrusion has been well exposed by recent logging and, at its margins, consists of fine-to medium-grained metagabbro. The core of the body consists of medium- to coarse-grained metamorphosed leucogabbro to gabbroic anorthosite, locally poikiloblastic. Continuous, regular igneous layers, 10 to 200 m thick are present in the body (Photo 10.2). Sulphide burns are common in the metamorphosed gabbro and leucogabbro units located near the margin of the body (Photo 10.3); assay results are pending. The igneous layering is cut by a variety of fine-grained mafic dikes, some of which are feldspar phyric and are likely part of the Matachewan dike swarm (2475 to 2455 Ma).

In terms of bulk-rock composition, grain size, and the presence of igneous layering, the Gerow Township intrusion resembles other members of the East Bull Lake intrusive suite. The presence of poikiloblastic leucogabbro near the margin of the Gerow Township intrusion is also a feature that has been observed near the margin of the Agnew intrusion (R.S. James, Laurentian University, personal communication, 2009). Although the age of this intrusion has not been determined, the similarity in rock types and textures, as well as the proximity to the East Bull Lake intrusion, all suggest that the Gerow Township is part of the East Bull Lake intrusive suite and, thus, Paleoproterozoic in age.

The relationship of the Gerow Township intrusion to the East Bull Lake intrusion is uncertain, especially given the coarse grain size and abundance of igneous layering in the relatively small Gerow Township intrusion. Is it part of the southern margin of the East Bull Lake intrusion that has been preserved due to faulting? Is it part of another East Bull Lake intrusive suite body that has been largely removed due to erosion? More interestingly, are there other, similar intrusions in the eastern part of the Whiskey Lake greenstone belt that have been mapped as Archean in age, simply because vegetative cover and overburden have hindered their recognition as members of the East Bull Lake intrusive suite?

## Dikes, Dikes and More Dikes: Unravelling the Long-Lived Magmatic History Preserved in the Archean Basement Adjacent To and Beneath the Quirke Lake Syncline

Previous maps of the area show that both the Whiskey Lake greenstone belt and the Archean granitic rocks located south of the greenstone belt are riddled with mafic dikes (Robertson 1961, 1962, 1968, 1970, 1977; Jensen 1992). The age and character of these mafic dikes was largely unknown. Preliminary data from several outcrop areas on Highway 108 south of Elliot Lake, which contain a multitude of mafic dikes of varied texture and composition, indicate that the majority of mafic dikes in the map area are part of the Matachewan dike swarm, although several other dike units are also present.

## MATACHEWAN DIKES

Dikes related to the Paleoproterozoic Matachewan dike swarm (2475 to 2455 Ma) are the most abundant mafic intrusive rock within the Archean basement. South of Elliot Lake, along Highway 108, Matachewan dikes constitute roughly 60 to 75% of the mafic dikes exposed in outcrop, whereas, on the east side of the map area, southeast of Whiskey Lake, this percentage rises to 90%. Several textural varieties are present within the Matachewan swarm dikes in the study area, but they fall into 2 broad



**Photo 10.2.** Igneous layering in the Gerow Township intrusion. From top to bottom, layers are medium-grained leucogabbro, anorthosite, medium-grained gabbroic anorthosite. Hammer handle is 40 cm long. Location: UTM 399813E 5134972N, NAD83, Zone 17.



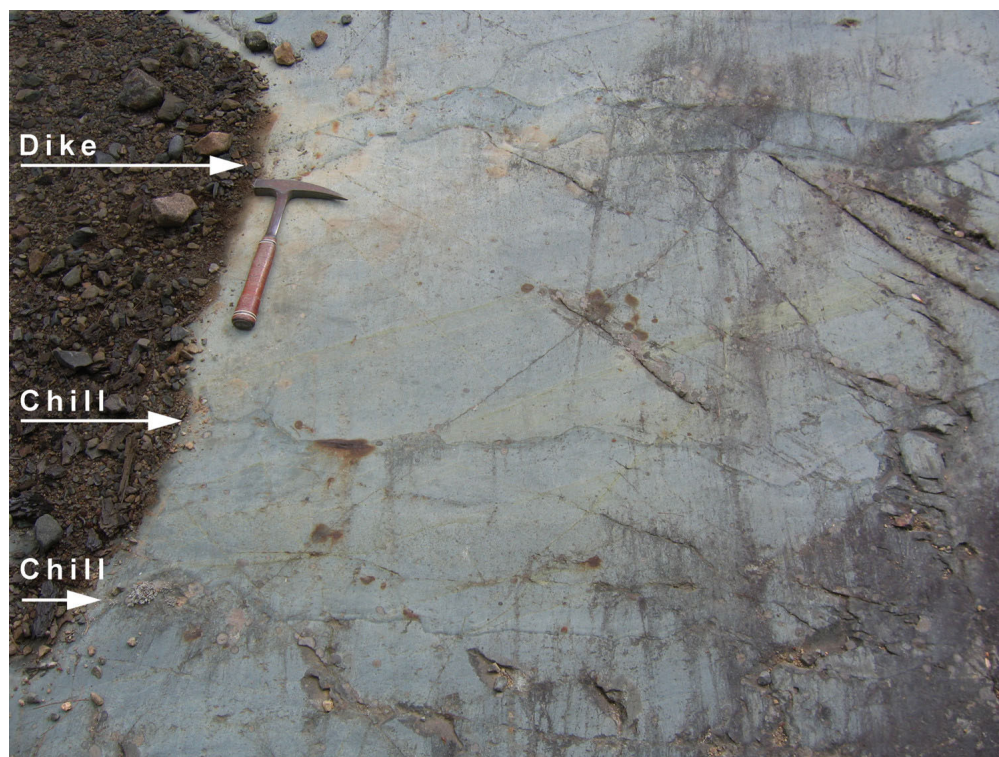
**Photo 10.3.** Sulphide burns in medium-grained leucogabbro of the Gerow Township intrusion. Hammer handle is 40 cm long. Location: UTM 399813E 5134972N, NAD83, Zone 17.

groups: non-phyric and plagioclase phyric. As documented in Tables 10.1 and 10.2, both the non-phyric and plagioclase-phyric dikes have similar scintillometer and whole-rock chemical signatures (e.g., in Table 10.2, compare samples 09RME-0055 and 09RME-0056). In the plagioclase-phyric dikes, the distribution of phenocrysts can vary greatly: in some dikes, phenocrysts are uniformly distributed throughout the dikes; in others, phenocrysts may be concentrated in either the cores or the margins. Phenocrysts can be laths, 1 to 3 mm in size, or glomerocrysts, 3 to 10 cm in size.

Composite dikes, resulting from repeated injections of magmas into the same fracture system, were observed in several parts of the study area. The composite dikes vary in width from 4 to 150 m, and can consist of a single textural type, or multiple textural types. They are recognized by the presence of thin chill zones parallel to the dike margin (Photo 10.4). In some cases, discrete, sharp-walled dikes are present, parallel to the main dike margin, and may have been emplaced later in the cooling history of the composite dike (*see* Photo 10.4).

## FEEDERS TO EAST BULL LAKE INTRUSIVE SUITE ROCKS

East-trending, medium-grained mafic dikes (*see* Table 10.2: sample 09RME-0029) within the Whiskey Lake greenstone belt exhibit geochemical signatures and rare earth element patterns intermediate between those of the Stone Ridge Intrusion (*see* Table 10.2: sample 09RME-0102) and the Matachewan dike swarm (*see* Table 10.2: samples 09RME-0055 and 09RME-0056). It is possible that these dikes may represent a common parental magma to both the East Bull Lake intrusive suite and the Matachewan dike swarm.



**Photo 10.4.** Composite Matachewan dike, single textural type. Note discrete dike by hammer head. Arrows point to chill contacts within the body of the dike, resulting from multiple injections of magma. At least 2 internal contacts are present in this 4 m wide dike, excluding the discrete dike by the hammer head. Hammer handle is 33 cm long. Location: UTM 385283E 5137798N, NAD83, Zone 17.

The abundance of Matachewan dikes, exhibiting a variety of textures, in the basement south of the map area, and, the geochemical similarity of some of these dikes to rocks of the East Bull Lake intrusive suite and the Thessalon Formation metavolcanic rocks, both indicate that these dikes are part of the magmatic system that feed both the Thessalon Formation and the East Bull Lake Intrusion.

## FEEDERS TO HURONIAN SUPERGROUP METAVOLCANIC ROCKS

On Highway 108, at distances of 100, 200 and 2200 m from the nearest exposures of Huronian Supergroup metavolcanic rocks, steep-walled, near-vertical, vesicular mafic dikes were observed cutting Archean mafic metavolcanic or granitoid rocks. The scintillometer signature of these dikes exhibits elevated potassium and thorium contents, similar to those observed in vesicular Huronian Supergroup metavolcanic flows (*see* Table 10.1). Major, trace and rare earth element geochemical data from these dikes indicate that indeed they are compositionally the same as the vesicular Huronian Supergroup metavolcanic flows (*see* Table 10.2: samples 09RME-00042 and 09RME-0073), having a bulk composition of medium-potassium basaltic andesite. Thus, the dikes were most likely feeders to the flows. These dikes are significant in that the presence of vesicles indicates that the dikes must be located near the old paleosurface on which the Huronian Supergroup flows were deposited, and that Huronian Supergroup metavolcanic rocks must have extended over a broader area than that indicated by current exposures (e.g., one dike is located 2.2 km south of the nearest Huronian Supergroup metavolcanic rocks).

No clearly recognizable feeders to the metabasalt flows present within the Huronian Supergroup were identified; however, the geochemistry of the Huronian Supergroup metabasalt flows is similar to that of the Matachewan dikes (*see* Table 10.2: samples 09RME-0056 and 09RME-0034), with similar rare earth element contents and patterns, except for the presence of a pronounced negative europium anomaly in the Huronian Supergroup metabasalts. The negative europium anomaly is consistent with plagioclase removal in the magma chamber to the metabasalts and, thus, there may be a genetic link between the Matachewan dike swarm and the Huronian Supergroup metabasalts.

## YOUNGER DIKES

A lamprophyre dike of unknown age was sampled on Highway 108 where it is emplaced into Archean granodiorite (*see* Table 10.2: sample 09RME-0074). The presence of lamprophyre dikes has been noted in mine workings in the Elliot Lake area, in association with Nipissing gabbro intrusions (Robertson 1961, 1962, 1968; Roscoe 1969), but they have not been reported cutting the Archean granitoid rocks.

An east-trending, plagioclase-phyric dike, with small (<2 mm), plagioclase laths was observed cutting a Nipissing metagabbro in Joubin Township west-northwest of Hough Lake (UTM 383316E 5141861N, NAD83, Zone 17). This dike is the only definitely post-Nipissing dike observed during mapping.

Although northwest-trending dikes of the Sudbury dike swarm (*circa* 1240 Ma) are common east of the study area near Bull and Agnew lakes, none were observed during the field season, confirming the observations of Robertson (1961, 1962, 1968).

**Table 10.3.** Field and drill-core criteria for discrimination of Archean versus Huronian Supergroup metavolcanic rocks.

Criteria	Archean	Paleoproterozoic (Huronian Supergroup)	Applicable to Drill Core?
<b>Texture</b>			
Pillows	Common, small to moderate, thin selvages (<0.5 cm)	Locally present, moderate to large, wider selvages (>0.5 cm)	No
Pillow basalt, hyaloclastite	Common	Uncommon	Yes
Vesicles	Uncommon	Large, quartz-filled, round to irregular, up to 5% of rock	Yes
<b>Structure</b>			
Foliation	Common, moderate to strong	Uncommon, typically weak	Yes, but not always easily
Veining	Common, thin quartz veins and white, fine-grained veins	Veining is generally uncommon	Yes
<b>Magnetic Susceptibility</b>			
	Metabasalt, typically <math>1.0 \times 10^{-3}</math> SI units	Metabasalts, typically <math>5.0 \times 10^{-3}</math> SI units Basaltic meta-andesite, typically >math>5.0 \times 10^{-3}</math> SI units	Yes
<b>Scintillometer</b> (see also Table 10.1)			
	Metabasalt, typically 0% K, 0 ppm U, 0 ppm Th	Basalts and basaltic meta-andesite, typically >0.5 % K, >4 ppm Th	No

## The Archean–Paleoproterozoic Unconformity

The unconformity between Archean rocks and the Huronian Supergroup is not well exposed on surface, and is generally only observed in diamond drill core. At the time of writing, the author had examined the unconformity in core from 8 diamond-drill holes located in Joubin and Gunterman townships. Access to core was provided Pele Mountain Resources, Appia Resources, and the Sault Ste. Marie Resident Geologist's Office, and the assistance of staff at all 3 organizations is greatly appreciated. In one core from Joubin Township, basal metaconglomerate of the Matinenda Formation rested directly on Archean mafic metavolcanic rocks. In core from the other holes, metamorphosed Thessalon Formation basalt or basaltic andesite flows rested directly on Archean metabasalt flows or metawacke, or there were thin units of metasandstone or metaconglomerate present between the Thessalon Formation rocks and the Archean basement. Contacts between the Huronian Supergroup metavolcanic and metasedimentary rocks and the Archean rocks are sharp. No paleosol was observed in any of the holes, although, in some instances, there was bleaching and minor alteration of the Archean rocks within 10 to 50 cm on the unconformity. In one hole, 4 flow units were present in the Thessalon Formation, each about 3 to 4 m thick. The flow units consist, from the unconformity upward, of a hyaloclastite unit, a perlitic-textured basaltic meta-andesite flow, and 2 vesicular basaltic meta-andesite flows, separated from one another by thin (30 to 50 cm) flow-breccia units.

The unconformity was observed at 2 localities on surface. The first is described below in "Livingstone Creek Formation". The other is located in Gaiashk Township (UTM 393822E 5138450N, NAD 83, Zone 17) in an area shown by Jensen (1992) as consisting entirely of Thessalon Formation rocks. Here, foliated, massive and wormy-textured Archean mafic metavolcanic flows are overlain subhorizontally by a massive, vesicular, basaltic meta-andesite flow. At this locality, the Archean and Huronian Supergroup metavolcanic rocks can be distinguished using the criteria listed in Table 10.3. It is possible that other exposures of the unconformity are present in the vicinity, given that flat-lying character of the Huronian Supergroup metavolcanic rocks; that is, topographic highs expose Huronian Supergroup metavolcanic rocks, whereas topographic lows expose Archean metavolcanic rocks.

## **FRACTURE FILLS, WEATHERED ROCKS AND PALEOSOLS**

At 2 localities, metasediment was observed filling fractures in underlying Archean mafic metavolcanic rocks approximately 500 m distant from the nearest exposures of Huronian Supergroup metasedimentary rocks. Modest potassium contents (0.5 to 2 weight %) in the fracture-filling metasediment suggests that they are locally derived and are not part of the Matinenda Formation, which would be expected to contain higher potassium contents (3 to 5 weight %). Just below the Discovery Site monument on Highway 108 (UTM 377868E 5138467N, NAD 83, Zone 17), a fracture, 3 m long and 2 to 7 cm wide, is filled with red-brown, slightly calcareous, fine- to coarse-grained metasediment containing abundant fragments of the adjacent fine-grained Archean mafic metavolcanic rock. The second site, located south of Pecors Lake (UTM 386602E 5137957N, NAD 83, Zone 17), is only exposed in plan view. There, the fracture is filled with coarse-grained metasediment. This site may be the one described in Jensen (1992).

No paleosol was observed during mapping, either on surface or in diamond-drill core; however, several sites of possible paleoweathering were observed. Most sites are located near Highway 108 south of Elliot Lake. At the best exposed site (UTM 376567E 5136603N, NAD 83, Zone 17), feldspars and amphibole in Archean granodiorite have been weathered to form either green- or red-weathering rock. This is not a recent weathering phenomenon, as the weathered rock is strong and competent. Chemical analyses from fresh and weathered rock are pending, and will assist in determining element mobility related to weathering. Scintillometer data at this site suggest a decrease in potassium from fresh rock (2.8 weight % K) to red rock (2.2 weight % K) to green rock (0.5 weight % K). Uranium and thorium show no significant change from fresh to weathered rock.

## **POTASSIUM, URANIUM AND THORIUM MOBILITY AT THE UNCONFORMITY**

Archean rocks in the study area are uniformly characterized by low thorium and uranium contents. In a few localized areas, either within a few tens of metres of the unconformity, or where till rich in Matinenda Formation metaconglomerate clasts overlies the basement, sporadic elevated values (10 to 20% higher than normal) of potassium, thorium and uranium were detected in Archean mafic rocks, or in Paleoproterozoic mafic dikes. Thus, there does not appear to be remobilization of thorium and uranium on a regional scale near the unconformity.

## **Elliot Lake Group**

The Elliot Lake Group consists of 3 formations: the metasedimentary Livingstone Creek Formation, the metavolcanic Thessalon Formation and the metasedimentary Matinenda Formation. Metavolcanic rocks on the north side of the Quirke Lake syncline have been called the Dollyberry Formation (Bennett, Dressler and Robertson 1991); however, there are no geochemical or lithological data to indicate that the metavolcanic rocks on the north side of the Quirke Lake syncline differ from those on the south side.

## **DISCRIMINATION OF HURONIAN SUPERGROUP AND ARCHEAN METAVOLCANIC ROCKS: FIELD AND DIAMOND-DRILL CORE CRITERIA**

Criteria for discriminating Archean versus Huronian Supergroup metavolcanic rocks are summarized in Table 10.3. Although many of these criteria that can be used on surface exposures, those applicable to diamond-drill core are more limited. The scintillometer was an effective discrimination tool on surface outcrops, but, unfortunately, it cannot be used on diamond-drill core. Mafic rocks are harder to discriminate than more intermediate composition rocks. Key features of the Huronian Supergroup basaltic andesitic metavolcanic rocks are their magnetic character and vesicularity.

## LIVINGSTONE CREEK FORMATION

Rocks potentially stratigraphically correlative with the Livingstone Creek Formation are exposed along the hydro transmission line west of Pecors Lake. Rusty-weathering heterolithic breccia (Photo 10.5a), lies unconformably on metamorphosed Archean pillow breccia, wacke and mudstone, and large (1 by 2 by 2 m) blocks of metawacke and metamudstone are present in the breccia. Breccia clasts are angular to subround. In addition to the presence of disseminated sulphides throughout the matrix of the breccia unit, locally, ovoid pyrite nodules, up to 10 cm in diameter, are present within the breccia unit. The abundance of angular clasts of the underlying rock units, some of which are metres in size, as well as the limited strike length of the breccia unit, suggest that it is locally derived, perhaps along a paleoscarp.

The breccia unit is overlain by metamorphosed massive and vesicular basaltic and basaltic andesite flows of the Thessalon Formation. The breccia unit is atypical of the Livingstone Creek Formation, as it lacks the abundant granitic fragments and sandy matrix that characterize the formation, but it is in the same stratigraphic position (i.e., below the Thessalon Formation) as the Livingstone Creek Formation. Whether this breccia unit is best assigned to the Livingstone Creek Formation, or should be designated as a member of the Thessalon Formation, remains to be determined.

At the time of writing, only a limited amount of diamond-drill core collected in 2007 and 2008 by Pele Mountain Resources along the southern margin of the Quirke Lake syncline had been examined by the author. In several cores, rocks potentially correlative with the Livingstone Creek Formation were observed, and include some thin metaconglomerate beds as well as some medium- to coarse-grained dark-coloured metasediments. Again, these units are not typical of the Livingstone Creek Formation, but they do lie between the Archean basement and the Thessalon Formation metavolcanic flows, and are potentially correlative with the Livingstone Creek Formation on the basis of stratigraphic position. Further diamond-drill core examination is planned.

Another breccia unit with a sulphide-bearing matrix that superficially resembles the aforementioned Huronian Supergroup breccia unit is exposed along an unnamed creek that enters Pecors Lake immediately west of Vite Point. The creek breccia differs in several critical aspects. First, it contains abundant metasediment fragments, up to 75 cm in diameter, which, on the basis of texture, composition,



**Photo 10.5.** a) Subrounded, broken, clasts from the Huronian Supergroup breccia unit along the hydro transmission line. Hammer handle is 33 cm long. Location: UTM 384826E 5137826N, NAD83, Zone 17. b) Arrows point to examples of rounded, intact, sandstone clasts from the Quaternary breccia unit near Vite Point. Scintillometer is 24 cm high. Location: UTM 387205E 5137790N, NAD83, Zone 17.

and scintillometer measurements, appear to belong either the upper Matinenda Formation or the Mississagi Formation. Neither formation was present at the time of Livingstone Creek Formation deposition. Second, the creek breccia contains subhorizontal layering where it is in angular contact with the underlying, sulphide-bearing, intermediate to felsic Archean metavolcanic basement rocks. Third, the creek breccia grades upward into the overlying tills; there is no unconformable relationship between the creek breccia and the till. Fourth, the matrix is not as indurated as the breccia unit along the hydro line, and all the clasts in the creek breccia are intact (Photo 10.5b) and can be removed whole with relative ease. In contrast, clasts in all of the Huronian Supergroup breccia and conglomerate units have broken surfaces that were polished during glaciation (compare Photos 10.5a and 10.5b). All of these observations suggest that the creek breccia is Quaternary and was partly lithified by precipitation of silica and sulphide derived from weathering of the neighbouring sulphide-rich rocks. Similar rocks formed by this process have been observed overlying marbles in the Grenville Province in southeastern Ontario (Easton 1987, p.87-88). Assay results from the underlying metavolcanic rocks, and the breccia matrix, are pending.

## **MATINENDA FORMATION**

Of all the Huronian Supergroup units, the Matinenda Formation received extra attention, due to the fact that all uranium deposits in the Elliot Lake area are hosted within it. In terms of stratigraphic height, from lowest to highest, the Matinenda Formation consists of 3 members: the Ryan, the Stinson and the Manfred members (Roscoe 1969). Due to lateral facies variations between the members, no continuous section is present through all 3 members, although, in parts of the area, the Stinson Member overlies the Ryan Member, and the Manfred Member overlies the Stinson Member. Only the Ryan and Manfred members contain mineralized conglomerates.

Along the south limb of the Quirke Lake syncline, west of Pecors Lake, the Ryan and Stinson members are 15 to 40 m and 20 to 30 m thick, respectively. The Ryan Member can be subdivided into several subunits (Cochrane, Hwozdyk and Hayden 2007): from lowest to highest, these are the Basal Conglomerate bed (0 to 11 m thick), the Divider quartzite (10 to 15 m thick), the Main Conglomerate bed, which consists of interlayered conglomerate and sandstone beds (2 to 3 m thick), and the Floater Reef quartzite zone (2 to 10 m thick). The Stinson Member consists of 2 newly recognized components: a lower green weathering, vitreous quartzite (15 to 20 m thick) and an upper white weathering, vitreous quartzite (15 to 25 m thick). All significant mineralization is found in the Main Conglomerate bed, but all parts of the Matinenda Formation contain thorium and uranium contents roughly twice that of average continental crust.

Within the study area, west of Pecors Lake, the Basal Conglomerate bed is only observed in diamond-drill core, and the Main Conglomerate bed is only exposed in 3 outcrop areas, one of which was exposed through surface stripping by Pele Mountain Resources. The Divider quartzite, the Floater Reef quartzite zone and both Stinson Member subunits are exposed in numerous localities. East of Pecors Lake, most of the Ryan Member is absent, due to the influence of paleotopography on deposition, with the lowest stratigraphic subunit being the Floater Reef quartzite zone. However, both subunits of the Stinson Member are present east of Pecors Lake.

## **LATERAL AND VERTICAL STRATIGRAPHIC VARIATIONS**

A significant difference between rocks of the Elliot Lake Group from the overlying 3 groups of the Huronian Supergroup (*see* Figure 10.2) is that the deposition of the Elliot Lake Group units was strongly influenced by the topography present on the Archean basement surface, and that the units exhibit considerable lateral and vertical facies variations. This is well illustrated by the distribution of the

**Table 10.4.** Scintillometer data for the Matinenda Formation on the southern limb of the Quirke Lake syncline. Stratigraphic subdivisions of the Ryan Member are from Cochrane, Hwozdyk and Hayden (2007). Stratigraphic subdivisions of the Stinson Member are from this study.

Rock Unit	n	K median (wt %)	U median (ppm)	Th median (ppm)	Total (cpm)	K (cpm)	U (cpm)	Th (cpm)	Magnetic Susceptibility ( $\times 10^{-3}$ SI units)
White, vitreous metasandstone, upper Stinson Member	33	0.6 (0.2–1.2)	8 (2–30)	19 (6–37)	655	81	49	17	0.04 median (0.01–0.07)
Green, vitreous metasandstone, lower Stinson Member	27	3.2 (2.4–5.8)	6 (2–15)	14 (6–41)	762	133	34	14	0.03 median (0.02–0.08)
Green, metasandstone and pebblestone, 'Floater-Reef Quartzite', upper Ryan Member (excluding Th-U layers)	23	4.3 (1.8–7.2)	43 (10–188)	102 (18–401)	3235	440	294	92	0.05 median (0.03–0.08)
Main Conglomerate Bed (mineralized), middle Ryan member	15	2.3 (0.0–5.0)	105 (42–413)	146 (49–364)	5836	812	621	133	0.33–0.92
Metasandstone of the 'Divider Quartzite', lower Ryan member	7	4.5 (2.8–7.4)	9 (8–18)	34 (21–61)	1278	230	78	33	0.07
Basal Conglomerate		n/a	n/a	n/a	n/a				no data

**Abbreviations:** cpm = counts per minute, n = number of samples, n/a = not analyzed, ppm = parts per million, wt % = weight percent.

**Notes:** multiply K by 1.2046 for  $K_2O$ , multiply U by 1.1793 for  $U_3O_8$ .

All K, U and Th data were recorded using an Exploranium™ GR-135G MiniSpec gamma-ray spectrometer, serial number 4885, calibrated on February 22, 2006, using an NaI crystal and software version 501GEO. The instrument was stabilized daily, and data were recorded using the assay mode with a 5-minute count time and an automatic dead time correction. Quoted accuracy is 0.1% K, 0.4 ppm U, and 0.7 ppm Th for a sample with 2% K, 2 ppm U and 8 ppm Th.

conglomerate beds of the Matinenda Formation, which show a north-northwest orientation likely reflecting deposition along original depositional channels. In contrast, strata of the overlying 3 groups were deposited with an easterly orientation, reflecting a platform developed adjacent to the Archean Superior Province. This is important with respect to exploration, as the orientation and composition of the overlying groups shows little to no correspondence with the distribution of the Elliot Lake Group.

## SCINTILLOMETER STRATIGRAPHY OF THE MATINENDA FORMATION AND POTENTIAL SUBDIVISION OF THE STINSON MEMBER

Within the Matinenda Formation along the south side of the Quirke Lake syncline, potassium content decreases with increasing stratigraphic height, as illustrated in Table 10.4. In the non-mineralized sandstone units, median uranium content is relatively constant throughout the formation at 6 to 9 ppm U, but median thorium decreases from roughly 34 ppm Th near the base of the formation, to roughly 17 ppm Th near the top of the formation. The decrease in potassium content most likely reflects decreasing clay content within the sandstone, and the decrease in thorium may reflect a decrease in detrital monazite content. Magnetic susceptibility shows minimal variation throughout the Matinenda Formation (see Table 10.4).

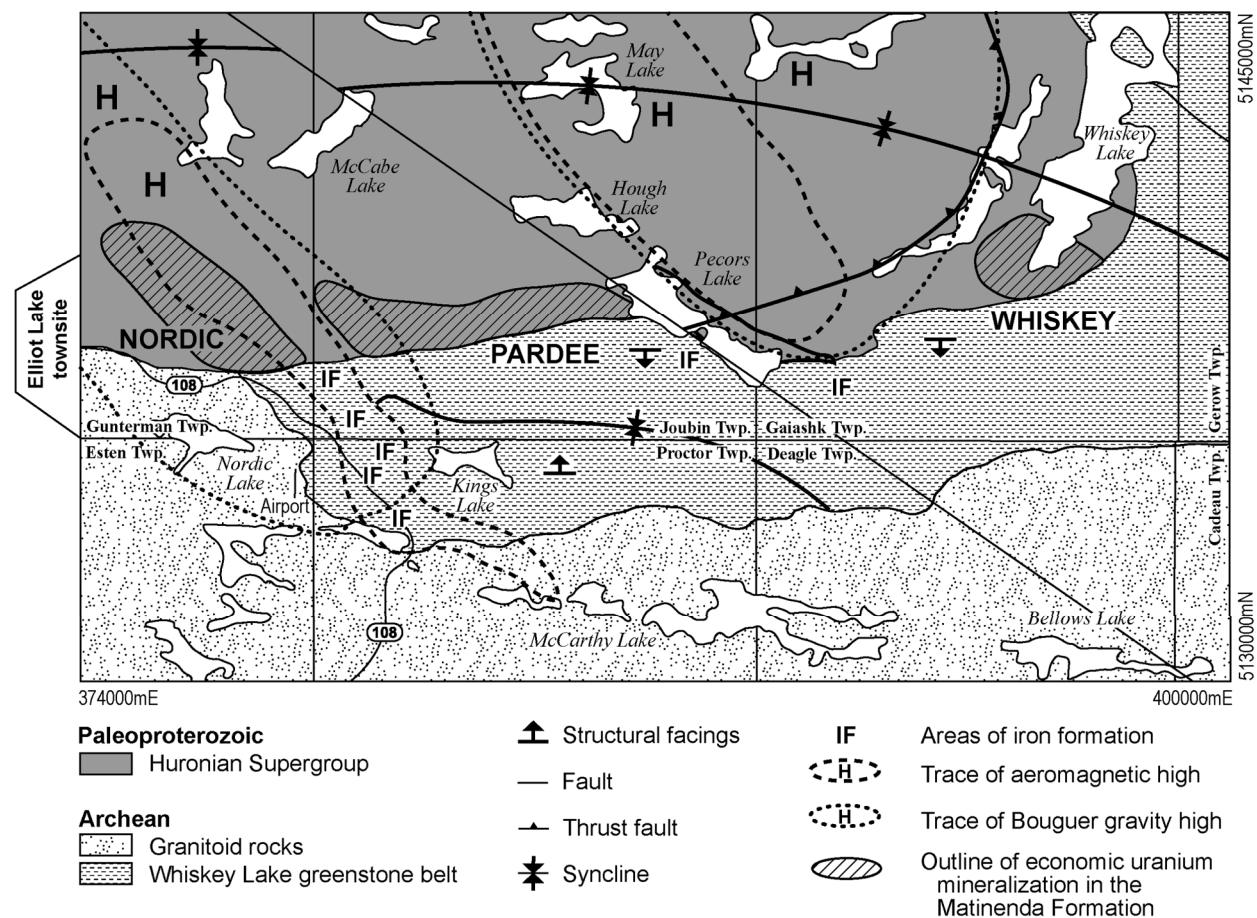
A dramatic decrease in potassium content occurs within the Stinson Member, with the metamorphosed greenish, vitreous sandstones of the basal half of the member having a median potassium content of 3.2 weight % K, whereas the whitish, vitreous sandstones of the upper half have a median

potassium content of 0.6 weight % K (see Table 10.4). This dramatic change in potassium content in the Stinson Member has not been reported in previous studies (e.g., Pienaar 1963; Roscoe 1969; Fralick and Miall 1982; Fralick, Miall and Abdel-Rahman 1986), most likely to the lack of sampling density in the Stinson Formation. The change in potassium content may reflect a change in sedimentation style or source region, or both, in the uppermost Stinson Member. Given that the lower potassium, white vitreous metasandstone can be mapped systematically throughout the study area, it may constitute either a new submember of the Stinson Member, or it may warrant designation as a new member of the Matinenda Formation. Additional geochemical, petrological and sedimentological studies of the low potassium metasandstone are needed before stratigraphic assignment can be ascertained.

## GEOPHYSICS

### Aeromagnetic and Bouguer Gravity Data

Two large, northwest-trending, coincident magnetic and Bouguer gravity highs dominate the regional magnetic and gravity pattern for the Pecors–Whiskey Lake greenstone belt (Figure 10.3). Previous workers (e.g., Robertson 1961, 1962, 1976) have attributed these anomalies to subsurface



**Figure 10.3.** Location of aeromagnetic and gravity highs in the Elliot Lake area and their relationship to zones of uranium mineralization. Quirke channel lies to the north of the area shown in the figure, between the 2 aeromagnetic and gravity highs. Channels from Robertson (1986). The UTM co-ordinates are provided using NAD83 in Zone 17.

exposures of iron formation; however, this interpretation seems unlikely. The regional structural trend within the Whiskey Lake greenstone belt is easterly, not northwesterly, and the exposed iron formation units in the belt consist of relatively lean magnetite-bearing rocks of limited extent. In addition, high-resolution aeromagnetic surveys over the southern margin of the Quirke Lake syncline, recently purchased by the Ontario Geological Survey (Rainsford and Muir, this volume), suggest that the large magnetic highs are deep seated, not the near-surface features that would be expected if the source were indeed iron formation. The easterly anomaly coincides with an area of non-deposition of both the Thessalon Formation and metaconglomerate of the Matinenda Formation (Roscoe 1969), suggesting that the location of this paleotopographic high may be linked to the source of the magnetic anomaly. The coincidence of magnetic and gravity highs suggests that they are related to higher density features at depth, such as large mafic intrusions. The abundance of Matachewan mafic dikes in the adjacent Archean basement, the distribution of Huronian Supergroup metavolcanic rocks, and the presence of large mafic intrusions such as the East Bull Lake and Agnew intrusions to the east of the study area, suggest that the source for these magnetic and paleotopographic anomalies may be a mafic intrusion(s) of early Paleoproterozoic age.

The main zones or channels containing economic uranium mineralization (Robertson 1976, 1986) (*see* Figure 10.3) are located on the east (Quirke and Whiskey zones) or the west (Pecors zone) flank of the eastern anomaly and on the east (Pardee zone) or the west flank (Nordic zone) of the western anomaly. The property currently being examined by Pele Mountain Resources includes both the Pardee and Pecors zones; however, so far, the best grades are located near the eastern flank of the western anomaly. If these magnetic anomalies in part reflect the distribution of paleotopographic highs that influenced Matinenda Formation sedimentation, then exploration should focus on the margins of these highs where mineralization has not been reported.

## **Airborne Gamma-Ray Spectrometric Data**

Most of the study area is covered only by low-resolution airborne gamma-ray spectrometer data (5 km line spacing) (Elliot, Holman and Richardson 1975). These data show weak potassium, thorium and uranium enrichment over the southern margin of the Quirke Lake syncline, but no localized highs. This is not surprising, even taking into account the low resolution of the data. First, overburden is extensive throughout this area and many of the overlying tills contain debris derived from the Matinenda Formation. Thus, the overburden both subdues the overall radiometric signature, but also creates a widespread, low-level anomaly related to the dispersion of mineralized rock. Second, and more important, the mineralized conglomerate horizon is moderately dipping, and relatively thin (<20 m thick), so even with no overburden and closer line spacing, this relatively thin, narrow target zone would still be difficult to detect using airborne methods.

## **MINERAL OCCURRENCES**

Although studied as recently as 2001 (Jobin-Bevans and Lyon 2001), the stripped areas and trenches associated with the Pecors nickel-copper prospect are now heavily overgrown, making detailed study of this prospect difficult. Based on the work on Jobin-Bevans and Lyon (2001), it appears that the prospect is hosted in Archean metavolcanic and metagabbroic rocks, and may be of volcanogenic magmatic sulphide rather than being a magmatic nickel-copper-PGE occurrence. Although located near the northern margin of the Stone Ridge Intrusion, there are no current data to suggest a direct linkage with that intrusion.

A high-purity quartz prospect in Deagle Township is being prospected by Rapiere Resources Incorporated (2001). A large test quarry is present at the site (UTM 395850E 5134880N, NAD 83, Zone 17) and much of the quartz body has been exposed by stripping. The prospect is located in the largest of

several north-trending quartz bodies present in Deagle Township (Robertson 1977), all of which are hosted in Archean granodioritic to granitic rocks. The age of the quartz body is Archean, as it is intruded by a mafic dike of the Paleoproterozoic Matachewan swarm. The quartz bodies shown by Robertson (1977) are located along a previously unrecognized north-trending structure, likely a fault, that extends as far north as Whiskey Lake, and which offsets magnetic trends in the Whiskey Lake greenstone belt. In Porter Township, north of Espanola, large quartz bodies are also found along north-trending structures in Archean granitic rocks (Easton 2006). Easton (2006) interpreted these north-trending structures as being the oldest faults present in that area, and the Archean age indicated for the Deagle Township body is consistent with that interpretation. Exploration for similar quartz bodies should focus where north-trending structures cut Archean granitic rocks.

## RECOMMENDATIONS FOR EXPLORATION

- Uranium exploration should focus on the margins of the 2 large northwest-trending magnetic highs present in the map area, particularly in areas where mineralization has not been reported, or where previous diamond drilling is limited.
- The discovery of additional intrusions related to the East Bull Lake intrusive suite in the study area enhances the exploration potential for contact-style nickel-copper-PGE mineralization in the area, in association with these intrusions.
- The presence of FII and FIII rhyolites in the Kings Lake area in the Whiskey Lake greenstone belt makes this area a base metal exploration target (*see also* Byron, Whitehead and Davies 1994).
- A sulphide-bearing interflow mudstone in the Thessalon Formation located on the Algoma–Nordic road (sample 09RME-0125: UTM 383972E 5137719N, NAD83, Zone 17) yielded the following assay results: 574 ppm Cu, 214 ppm Pb and 1006 ppm Zn. Nickel content was low (26 ppm). This combination of anomalous concentrations of copper, lead and zinc in a possible exhalative unit suggests that the mafic metavolcanic rocks of the Thessalon Formation may have potential for hosting volcanogenic massive sulphide–style base-metal mineralization.
- Exploration for high-purity quartz bodies should focus where north-trending structures cut Archean granitic rocks.

## ACKNOWLEDGMENTS

Pele Mountain Resources Inc. and Appia Resources provided access to diamond-drill core from their properties. A. Pace assisted in accessing historic diamond-drill core stored at the OGS Resident Geologist's Office in Sault Ste Marie.

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# 11. Project Unit 08-021. Mesoproterozoic Midcontinent Rift–Related Mafic Intrusions Near Thunder Bay: Update

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## INTRODUCTION

This ongoing project has been most recently summarized by Smyk et al. (2008). Mafic sills and dikes, extending over 300 km from south of Thunder Bay to northeast of Lake Nipigon, represent the northern expression of the Mesoproterozoic Midcontinent Rift. The sills had previously been collectively referred to as the Logan sills and, until recently, were considered to be a relatively homogeneous package of rocks (Stockwell et al. 1970). Work conducted as part of the Lake Nipigon Region Geoscience Initiative (LNRGI) showed that the sills in the vicinity of Lake Nipigon can be subdivided into a number of discrete units with distinct geochemical and isotopic characteristics (Hollings et al. 2007a, 2007b; Heaman et al. 2007) (Figure 11.1). This work also suggests a geochemical difference between the sills to the north and south of Thunder Bay (Hart 2003; Hart and MacDonald 2007; Hollings et al. 2007a) (*see* Figure 11.1). It has been proposed that the term Logan Igneous Suite, a component of the Midcontinent Rift Intrusive Supersuite (Miller et al. 2002), should be collectively applied to all the diabase sills in the area north of Lake Superior, with subdivision into more informal geochemical subdivisions (i.e., Nipigon sills for the sills north of Thunder Bay, and Logan sills for those to the south) (Figure 11.2).

In addition to these voluminous sill suites, there are a number of discrete mafic and ultramafic intrusions and dike swarms that represent both some of the oldest and the youngest Midcontinent Rift magmatism on the north shore of Lake Superior (Heaman et al. 2007; Smyk, Hollings and Heaman 2006) (*see* Figure 11.2; Table 11.1). Although the intrusions north of Thunder Bay were extensively studied during the LNRGI, those south of Thunder Bay have received limited study in the past few decades, despite the presence of nickel-copper mineralization in some of these intrusions (e.g., Crystal Lake gabbro).

## PROJECT UPDATE

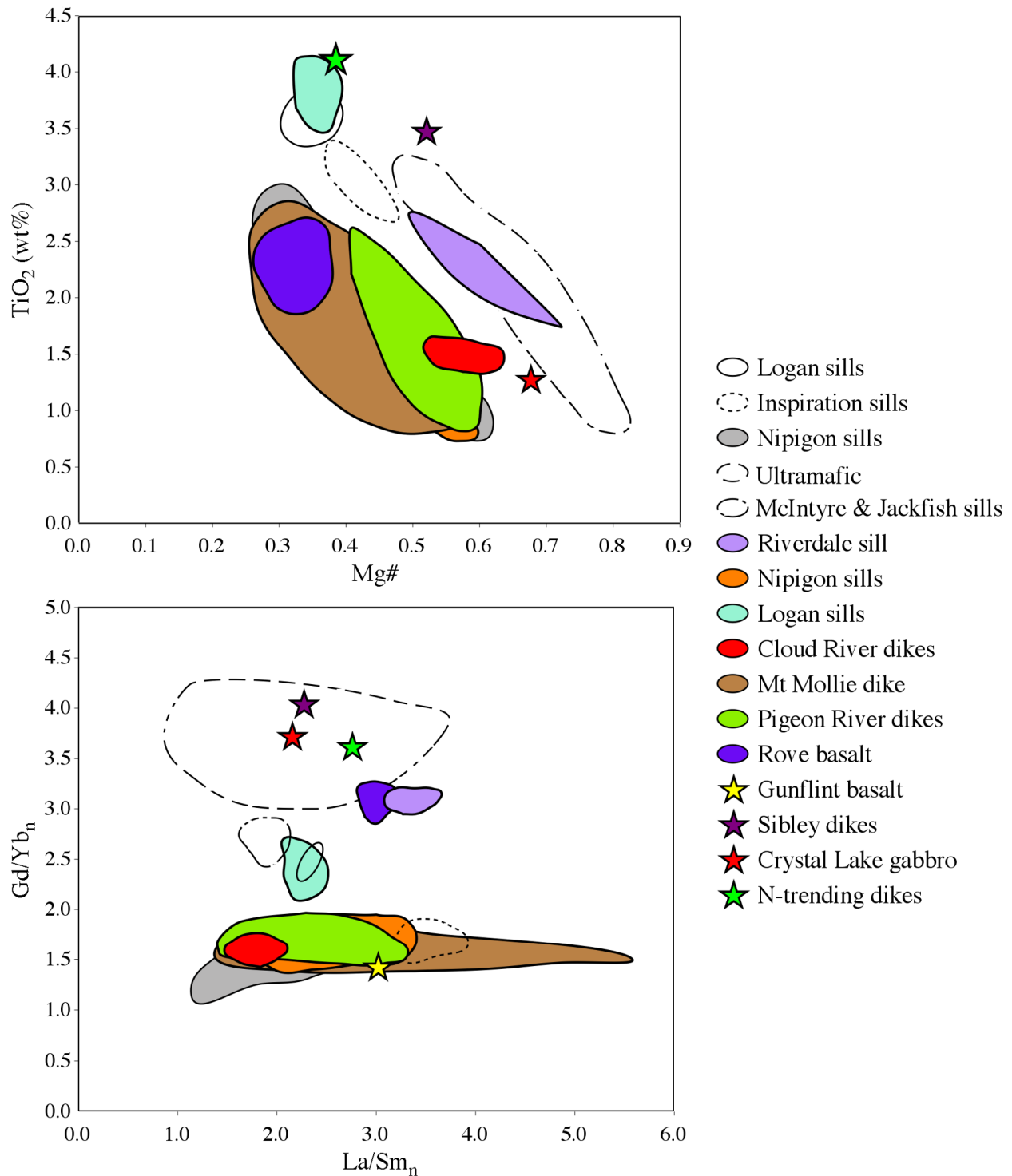
A Miscellaneous Release—Data (Smyk and Hollings 2009) contains results of geochemical analyses on bedrock and diamond-drill core samples collected between 1999 and 2008 (Hollings, Smyk and Hart 2007; Hollings and Smyk 2008). A total of 267 samples were collected from a number of intrusions (*see* Table 11.1) on the Black Bay and Sibley peninsulas and around Thunder Bay, primarily to the south and west of the city.

In order to fully characterize and subdivide the mafic intrusions near Thunder Bay and to allow comparison with the sills identified around Lake Nipigon as part of the LNRGI (Heaman et al. 2007; Hollings et al. 2007a, 2007b), a representative subset of 34 samples were analyzed for Rb–Sr and Sm–Nd isotopes and reported in Smyk and Hollings (2009).

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*Summary of Field Work and Other Activities 2009,  
Ontario Geological Survey, Open File Report 6240, p.11-1 to 11-5.*

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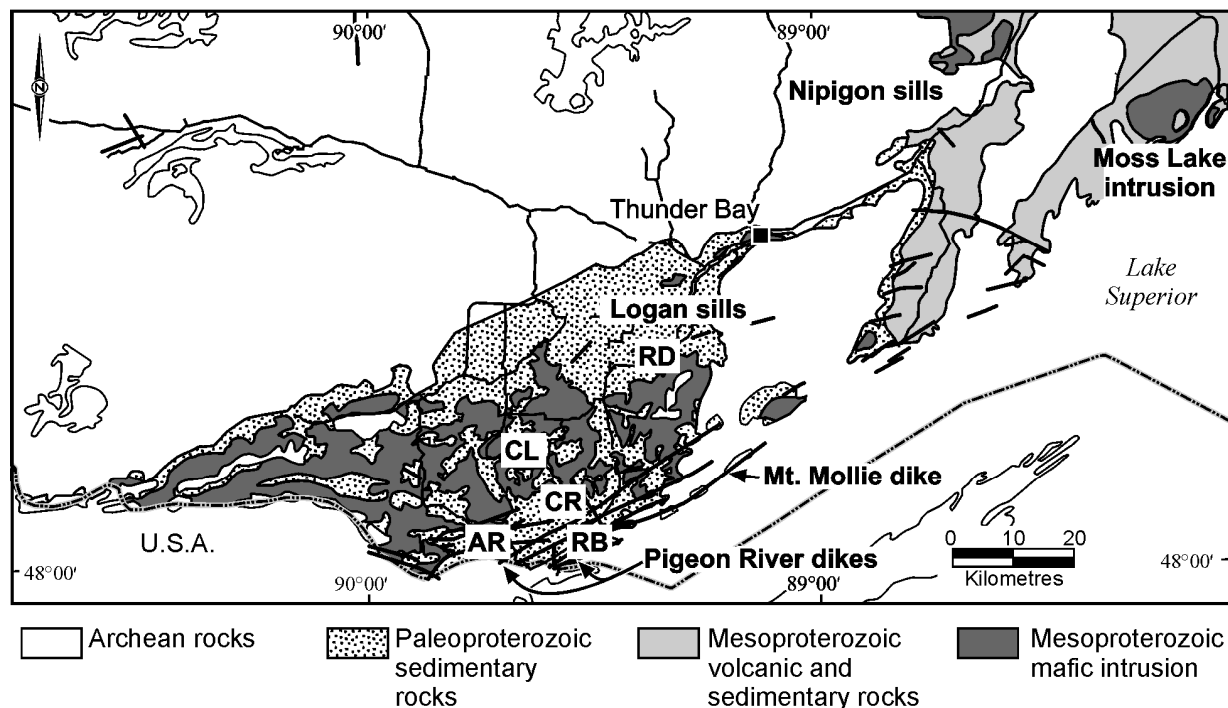
**Figure 11.1.** Major and trace element variation diagrams illustrating the geochemical affinities of the sills south of Thunder Bay. Dashed and grey scale fields are from older data sets, whereas coloured fields are from this study. Older data for Logan sills are from Hart (2003, 2005). Nipigon data are from Hollings et al. (2007a). Older data for dikes south of Thunder Bay are from L. Hulbert and R. Ernst (Geological Survey of Canada, personal communication, 2006) from samples collected by M. Smyk and J. Scott (Resident Geologist Program, Ontario Geological Survey), and from Hollings, Smyk and Hart (2007).

In addition to geochemical studies, this project also incorporated a paleomagnetic study, the results of which were reported in Smyk et al. (2008). In order to better characterize the intrusive suites, 4 new ages were obtained by L.M. Heaman of the University of Alberta (L.M. Heaman, University of Alberta, personal communication, 2009). The ages reported here supersede those reported by Hollings et al. (2009). A northwest-trending Cloud River dike (DB20) yielded a  $^{206}\text{Pb}/^{238}\text{U}$  age of  $1109.2\pm 4.2$  Ma. A sample from the Pine Point–Mount Mollie dike (DB58) yielded a  $^{207}\text{Pb}/^{206}\text{Pb}$  age of  $1109.3\pm 6.3$  Ma. Small baddeleyite grains from a plagioclase-megacrystic unit in drill core with Logan sill-like affinity (DB196) yielded a  $^{207}\text{Pb}/^{206}\text{Pb}$  age of  $1088\pm 20$  Ma. Zircon from the Current Lake peridotite (DB265) yielded an age of  $1120\pm 23$  Ma.

**Table 11.1.** Listing of intrusions sampled in the Thunder Bay area. The data for the Current Lake peridotite are previously unpublished.

Intrusion	Location	Lithology	Age (Ma)	Source
Moss Lake	Black Bay Peninsula	quartz norite, norite, ferrogabbro	$1094.7\pm 3.1$	Heaman et al. (2007)
Logan Sill	South of Thunder Bay	quartz-tholeiitic diabase	$1114.7\pm 1.1$	Heaman et al. (2007)
Nipigon Sills	North and south of Thunder Bay	olivine-tholeiitic diabase	$1106.8\pm 1.9$ to $1112.7\pm 2.4$	Heaman et al. (2007)
Riverdale Sill	South of Thunder Bay	gabbro-norite	<i>No suitable material</i>	Hollings et al. (2009)
Pigeon River dikes	South of Thunder Bay; Black Bay Peninsula(?)	northeast-trending olivine diabase	$1141\pm 20$ ; $1078\pm 3$	Heaman et al. (2007)
Cloud River dikes	South of Thunder Bay	northwest-trending olivine diabase	$1109.2\pm 4.2^*$	this study
Crystal Lake Gabbro	Pardee Township	layered gabbro, anorthosite	$1099.6\pm 1.2$	Heaman et al. (2007)
Pine Point–Mount Mollie Dike	Crooks Township and offshore islands	east- to northeast-trending gabbro and granophyre	$1109.3\pm 6.3$	this study
Current Lake	North of Thunder Bay	peridotite	$1120\pm 23$	this study

\* Originally reported as  $1132.2\pm 15.9$  Ma in Hollings et al. (2009) on the basis of a limited data set.



**Figure 11.2.** General geology of the study area, showing distribution of Logan and Nipigon sills and sampled intrusions. Abbreviations: AR, Arrow River dike; CL, Crystal Lake gabbro; CR, Cloud River dike; RB, Rita Bolduc dike; RD, Riverdale Quarry sill.

## DISCUSSION OF RESULTS

The whole rock geochemistry (*see* Figure 11.1) of the gabbroic sills to the south of Thunder Bay supports earlier observations by Hollings and Smyk (2008) that Logan sills predominate in this area, with the exception of the recently recognized Riverdale sill. In contrast, the majority of the dikes analyzed are geochemically comparable to the Nipigon sills reported by Hollings et al. (2007b) suggesting that they do not represent feeders for the Logan sill complexes. However, limited data suggest that there is no significant geochemical difference between the Pigeon River, Cloud River and Mt. Mollie dike suites, despite their different orientations and reported ages.

Logan sills are distinguished from the other sill suites by their relatively high TiO<sub>2</sub> values (ranging from ~3.3 to 4.0%) and low Mg# values (ranging from ~0.3 to 0.45; *see* Figure 11.1). In contrast, the Riverdale sill displays a higher range in Mg# (~0.5 to 0.75) and lower TiO<sub>2</sub> values, comparable to the majority of the other mafic intrusions. Plots of Gd/Yb<sub>n</sub> versus La/Sm<sub>n</sub> reveal distinct rare earth element (REE) compositional ranges for the major intrusive suites. They also suggest that the Riverdale magma was derived from a more primitive source than the other magmas. Detailed studies, as part of a BSc thesis, were initiated on the Riverdale sill in 2009 by R. Puchalski (undergraduate student, Lakehead University, Thunder Bay).

Two additional units have also been recognized: a suite of north-trending dikes, which are geochemically similar to the ultramafic intrusions in terms of their TiO<sub>2</sub> and Mg#, but comparable to the Logan sills in terms of their REE (*see* Figure 11.1); and a second suite of dikes, located on the Sibley Peninsula, that are geochemically comparable to the ultramafic intrusions of the Lake Nipigon area (*see* Figure 11.1). Additional work will be necessary to better constrain these suites and place them within the stratigraphy of the Midcontinent Rift.

An enigmatic lithologic unit, described as Rove Formation basalt by Tanton (1936), was investigated in 2008 and 2009. Scattered outcrops in central Devon Township reveal basaltic andesite flow units which are locally vesicular, amygdaloidal and spherulitic, and display ropy flow tops. The flows appear to conformably overlie Paleoproterozoic Rove Formation shales and sandstones. It is not apparent what lithologic unit overlies the flows. Attempts to determine a reliable age on this unit have been problematic as no suitable material was recovered from the one sample submitted for geochronological analysis.

Detailed studies, as part of a BSc thesis, were also initiated on these volcanic rocks in 2009 by R. Cundari (undergraduate student, Lakehead University, Thunder Bay). The geochemistry of these volcanic rocks distinguishes them from the majority of the intrusive suites and also from a basaltic unit that occurs near the base of the Paleoproterozoic Gunflint Formation nearby. Initial geochemical results suggest that the basaltic unit in Devon Township may also occur over 20 km to the west-northwest in Hardwick Township, where similar rocks overlie Rove Formation shales and are overlain by Logan diabase. Additional samples were taken in 2009; analytical results are pending.

Further studies will focus on delineating the extent of these aforementioned volcanic rocks, as well as on interpreting the whole rock and isotopic geochemical results obtained so far. These data will help to refine the tectonomagmatic model for this part of the Midcontinent Rift.

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# 12. Project Unit 09-006. Western Wabigoon Subprovince Synthesis Project

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<sup>1</sup>Precambrian Geoscience Section, Ontario Geological Survey

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## INTRODUCTION

This contribution describes a new, multi-year project to synthesize the geology of the western Wabigoon Subprovince. Activities carried out in 2009 are largely devoted to compiling existing data; however, some initial field work was undertaken. The rationale and objectives of the study are discussed below, followed by some preliminary results from this field work.

## RATIONALE FOR SELECTING AREA

Few areas of exposure of Archean crust have influenced our understanding of Archean crustal evolution as much as the western Wabigoon Subprovince and adjacent portions of the Winnipeg River and Quetico subprovinces. The area first emerged as a benchmark in Archean geology with the pioneering work of Lawson (1885, 1913) who identified and described relationships between metavolcanic rocks (Keewatin series), older (Laurentian) meta-igneous rocks and younger (Algoman) plutons. Pettijohn (1935, 1936, 1943) was among the first to demonstrate that Archean supracrustal rocks were amenable to detailed sedimentological and stratigraphic analysis. During the 1970s, multidisciplinary investigations carried out by the Centre for Precambrian Studies (University of Manitoba) and Superior Geotraverse Group (University of Toronto) pioneered the integration of geological and geophysical methods as applied to Archean cratons. Several of the first attempts to interpret the evolution of Archean crust within a plate tectonic paradigm were based largely on consideration of geological relationships within the area (Langford and Morin 1976; Blackburn 1980). Much of the western Wabigoon Subprovince is well exposed and has been mapped by the Ontario Geological Survey and its predecessor organizations in comparative detail (for references, *see* Blackburn et al. 1991). Portions of the area were among the first where modern high-precision U/Pb geochronological investigations were carried out in conjunction with mapping. The area is also exceptional from the point of view of the Archean plutonic record as it is one of the few areas where all components of this record have been identified and studied.

Although the western Wabigoon Subprovince is arguably one of the better mapped and understood Archean greenstone–granite terranes, there is potential to improve on this understanding for a number of reasons:

- some of the mapping requires updating with some areas having last been mapped over 50 years ago
- level of detail available for different aspects of the geology (e.g., structure, metamorphism) is erratic across the region

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*Summary of Field Work and Other Activities 2009,  
Ontario Geological Survey, Open File Report 6240, p.12-1 to 12-6.*

- additional or “first pass” geochronological investigations are required in portions of the area
- modern lithogeochemical data are only available for selected areas
- almost all of the area now has detailed coverage from airborne magnetic and electromagnetic surveys

In addition to the foregoing, several investigations already underway (Beakhouse, this volume; Stone, this volume) will provide data and interpretations in support of a regional synthesis, as will several other projects being planned pending availability of resources.

The western Wabigoon Subprovince hosts numerous past-producing gold deposits, mostly dating from the first half of the last century, but none were major producers. Only one major past-producing base metal deposit (Mattabi) lies within the area. The region is also known to host a variety of other commodities including nickel-copper-platinum group metals, rare metal pegmatites and building stone. Results from a recent resurgence in mineral exploration, including a number of advanced exploration projects, have led to the discovery of new zones and delineation of significant resources (*see* Ravnaas and Bongfeldt (2008) and Ravnaas, Raoul and McDonald (2007) for summaries of recent exploration activities) further suggesting that this region has significant mineral exploration potential.

## OBJECTIVES AND PERSONNEL

The objective of the western Wabigoon Subprovince synthesis project is to compile existing data, integrate results from ongoing parallel mapping and thematic studies and upgrade our regional understanding of the area, especially with regard to structure, geochronology, lithogeochemistry, granite petrology and controls on mineral deposits. Results will be released primarily as a geographic information system (GIS) product; however, reports and compilation maps (likely at a nominal scale of 1:100 000) will be released periodically as the synthesis of different subareas are completed.

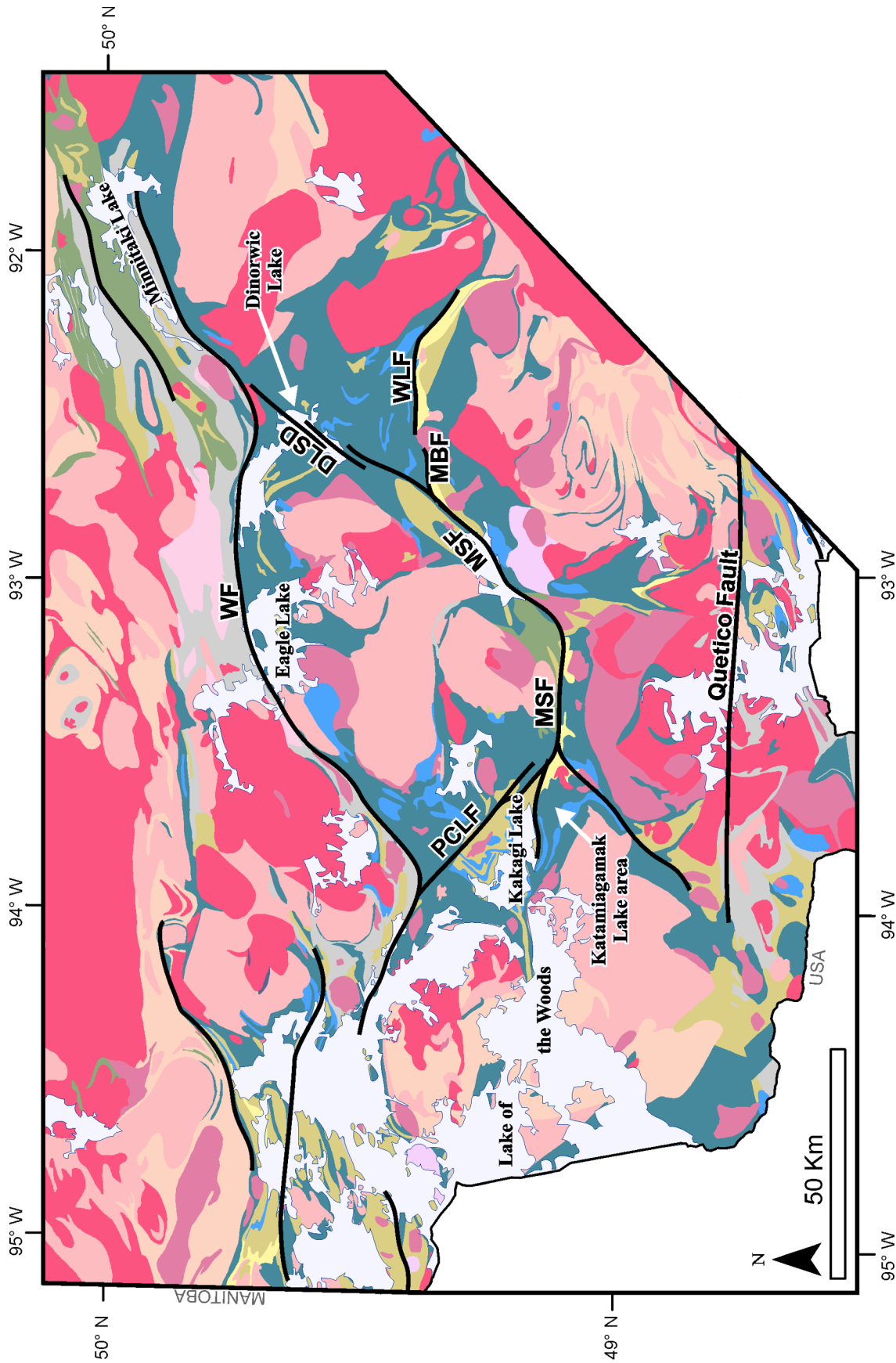
In addition to Ontario Geological Survey Precambrian Geoscience Section geoscientists (G.P. Beakhouse, D. Stone, D.R.B. Rainsford, possibly others), other contributions to the project include GIS support (S.D. Josey, J.L. Webb: Precambrian Geoscience Section) and regional geology and mineral deposit studies (C. Ravnaas, D. Scholtz: Resident Geologist Program, Ontario Geological Survey).

## OBSERVATIONS FROM 2009 FIELD WORK

This section reports some observations and preliminary interpretations based on field work carried out in 2009. Much of this field work was carried out within an approximately 2500 km<sup>2</sup> area centred approximately on Dinorwic Lake, with limited additional work being carried out in several other areas, notably in the Katamiagamak Lake area (Figure 12.1). Some area specific and thematic results from this work are discussed below.

### Stratigraphy and Structure East of Dinorwic Lake

The timing and stratigraphic affinity of a complexly deformed, dominantly mafic metavolcanic sequence lying to the east of the Dinorwic Lake structural domain, south of the Wabigoon fault and north of the Mosher Bay–Washeibemaga Lake fault (*see* “Regional Fault Systems”) is poorly understood. Volcanic rocks in the southern portion of this area have been referred to as the Boyer Lake volcanics (Trowell, Blackburn and Edwards 1980); however, the northern boundary of this unit is imprecisely



**Figure 12.1.** Geologic map of the western Wabigoon Subprovince illustrating the location of some of the major faults and deformation zones. Abbreviations: DLSD, Dinorwic Lake structural domain, MBF, Moshier Bay fault; MSF, Moshier Bay fault; PCLF, Pipestone-Cameron Lakes fault; WF, Wabigoon fault; WLF, Washebenmaga Lake fault.

defined. An initial attempt to determine the age of the Boyer Lake volcanics (approximately 2703 Ma: Davis, Blackburn and Krogh 1982) was subsequently reinterpreted as a porphyry intrusive age and a U/Pb zircon age of  $2722 \pm 5$  Ma for a gabbro sill (Davis 1989) provides a minimum age constraint on the timing of volcanism for this portion of the area. A single unpublished age determination of 2730 Ma from the eastern portion of the Raleigh Lake belt (*see* Stone, this volume) is similar to ages reported for the Wabigoon volcanics. It is not clear if portions of the volcanic stratigraphy correlate with the Wabigoon volcanics to the west or to what extent volcanic units associated with the southern volcanic belt of the Sioux Lookout belt, the Raleigh Lake belt and Kawashegamuk Lake area (to the northeast, east and southeast, respectively) that appear to correlate with portions of the stratigraphy may be distinct lithostratigraphic units. The regions where these relatively simple stratigraphic belts merge with the main mass of the greenstone belt area are characterized by structural complexity (e.g., Berger 1989). Given this complexity and the limited constraints on the timing of these sequences, it is not clear whether volcanic rocks in this area are representative of a single volcanic assemblage or how they regionally correlate with other portions of the western Wabigoon Subprovince. Additional geochronology and lithochemistry will be required to evaluate this complexity and make regional correlations.

## Regional Fault Systems

One of the most striking structural features of the western Wabigoon Subprovince is a series of variously oriented faults that occupy the central portion of many metavolcanic–metasedimentary belts and appear to form an interconnected, anastomosing system (*see* Figure 12.1). The Wabigoon fault is a major structure that has been interpreted as a terrane boundary separating 2 domains with contrasting stratigraphy and structural style (Beakhouse et al. 1995). The Manitou Straits fault trends to the southwest from Upper Manitou Lake to the Manitou Stretch area from where it trends west to the Pipestone Lake area. The fault has been interpreted to extend in a northeasterly direction from Upper Manitou Lake through the Dinorwic Lake area and possibly merging with the Wabigoon fault (Trowell, Blackburn and Edwards 1980); however, this study and earlier mapping (Beakhouse and Idziszek 2006) recognize the Dinorwic Lake area as being characterized by strong fabric development and extensive alteration in a series of left-stepping, *en échelon* zones, but with no clear, throughgoing zone of simple shear. An alternative interpretation requiring further testing is that the fault merges with the easterly trending Mosher Bay–Washeibemaga Lake fault in the Upper Manitou Lake area and that zones of strong fabric development and/or deformation between Upper Manitou Lake and the north end of Dinorwic Lake accommodate differential movement on the Wabigoon and Manitou Straits–Mosher Bay fault systems, but may not reflect a major, throughgoing zone of simple shear.

Similarly, in the Pipestone Lake area, the Manitou Straits fault has been interpreted to merge with the northwest-trending Pipestone–Cameron lakes fault which links with the Wabigoon fault near Dogpaw Lake. Alternatively, the fault may merge with southwest-trending structures in the Pipestone–Burditt lakes belt (Blackburn, Beard and Rivett 1981) or continue (with a minor inflection) in a westerly direction though a zone of high strain identified during this study near the southern shore of Kakagi Lake. There is presently insufficient data to assess which of these structures are major zones of simple shear having significant displacement.

## Controls on Gold Mineralization

A number of areas of historical gold occurrences and/or areas of active exploration were examined during the course of field investigations. Individual occurrences have many differences in detail and it is beyond the scope of this report to describe these. The intent of the discussion below is to highlight some recurring themes that are noted in all of the occurrences examined.

A common recurring theme for gold mineralized systems in the western Wabigoon Subprovince is a close spatial association with lithologic contacts between units having pronounced ductility contrast. The ductility contrast arises both from primary characteristics of the units and differential susceptibility to secondary alteration. Examples of juxtaposed lithologies giving rise to ductility contrast observed include mafic metavolcanic–felsic metavolcanic (e.g., van Horne township prospects, Sakoose Mine), mafic metavolcanic–felsic porphyry (Porphyry, Howie Lake occurrences), felsic metavolcanic–metasedimentary (e.g., Thunder Lake prospect), unaltered felsic intrusive–sericitized felsic intrusive (e.g., St Anthony Mine (*see* Beakhouse, this volume)). This is not an exhaustive list with other potential associations giving rise to ductility contrast including, for example, ironstone or cherty chemical sedimentary units in contact with metavolcanic or metasedimentary rocks, contacts between massive gabbroic and finer grained, altered mafic metavolcanic units or the contacts between plutons and their country rocks. During deformation, the ductility contrast is interpreted to facilitate heterogeneous strain resulting in some combination of brittle failure within more competent units, more intense fabric development within more ductile units and simple shear at contacts.

In some cases, there are inflections in regional stratigraphic and/or structural trends associated with these zones of higher overall strain that may originate in response to the heterogeneous nature of strain. The presence of secondary alteration and/or veining indicates that zones of heterogeneous strain have served to focus hydrothermal fluid flow.

In many cases, altered and mineralized zones coinciding with heterogeneously strained zones of lithologic complexity occur near, though not directly on, major regional fault systems. Structures associated with the zones of heterogeneous strain may develop as splays that are physically connected to major structures. However, these zones of heterogeneous strain may also be discrete zones related to deformation on major structures without obvious physical continuity with those structures. For example, mineralized shear zones at lithologic contacts in southern van Horne Township are not apparently physically linked to the Wabigoon fault (5 km to the north), but they have similar shear sense indicators and fabric orientations and are interpreted to be different manifestations of the same deformational processes.

Tectonic structures are the primary control on the localization of mineralization by focussed hydrothermal fluid flow and understanding the location, geometry and origin of these structures is critical. Unfortunately, mineral exploration is hampered by the fact that these structures are not consistently distinguished on existing geological maps. If the foregoing arguments are correct, this suggests that a simply applied grassroots exploration and/or prospecting strategy might involve identification of zones of lithological complexity, which generally are identifiable on existing bedrock maps, and rapidly assessing these for evidence of heterogeneous strain and hydrothermal alteration. Proximity to large-scale regional fault systems, and particularly portions of these structures that are characterized by regional-scale inflections and/or the presence of higher order related structures, may also be criteria for area selection.

## ACKNOWLEDGMENTS

Craig Ravnaas and Joanne Bongfeldt (Resident Geologist Office, Kenora) generously provided ongoing logistical, technical and scientific support. Denver Stone reviewed an early version of this report and shared his ideas in numerous informal discussions pertaining to various aspects of Wabigoon Subprovince geology. Much insight was gained from discussions and field trips with prospectors and geologists working in the area, notably Alex Glatz, Joe Riives, Patrick Lengyel and Cam Rennie (Laurentian Goldfields Ltd.), Alasdair Mowat (Pacific Iron Ore Corporation), and Scott Jobin-Bevans and Rory Krockner (Treasury Metals).

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# 13. Project Unit 00-012. Investigations of Granitoid Rocks in the Wabigoon Subprovince

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## INTRODUCTION

Several weeks of field work were devoted to examination and sampling of intermediate to felsic intrusive rocks within the western Wabigoon Subprovince. These activities constitute part of a broader, thematic, pan-provincial examination of intermediate to felsic plutonism and its relationship to mineralization, with a particular emphasis on gold mineralization systems. Work completed under this project in a variety of areas have lead to the formulation of a working hypothesis that links diverse petrogenetic suites of intermediate to felsic intrusive rocks to the tectonic evolution of the Superior Province and gold mineralized systems to structures and a distinctive suite of mantle-derived intermediate plutons associated with an extensional orogenic collapse stage of tectonic evolution (Beakhouse 2007a, 2007b).

Field investigations carried out in the Wabigoon Subprovince during 2009 focussed on 2 general problems: contact relationships at the margins of large granitoid complexes and general characteristics of selected discrete plutons. In addition, controls on gold mineralization in several areas where mineralization is spatially associated with intermediate to felsic intrusive rocks are discussed in a companion paper as part of the more general issue of gold mineralization control in the western Wabigoon Subprovince. The locations of areas discussed are illustrated in Figure 13.1 and each of these general topics are discussed separately below.

## BATHOLITH CONTACT RELATIONSHIPS

Contact relationships between large batholithic complexes and the greenstone belt were investigated along the northeastern margin of the Atikwa batholith and the southeastern margin of the Aulneau batholith. Both batholiths are large, complex multiphase complexes. Previous investigations indicate that both batholiths are synvolcanic and have a high-aluminum tonalite–trondhjemite–granodiorite (TTG) petrogenetic affinity (Davis and Edwards 1982, 1986; Davis, Blackburn and Krogh 1982; Edwards and Davis 1991; Beakhouse and McNutt 1991). Despite these broad similarities, contact relationships in these 2 areas are quite distinct.

The northeastern contact of the Atikwa batholith is characterized by an abundance of fine- to medium-grained dikes spanning a broad composition ranging from mafic to felsic. In the absence of large, good exposures, it is commonly difficult to differentiate dikes from finer grained portions of the batholith or from fine- to medium-grained metavolcanic rocks with the result that, in many areas, it is only possible to define a contact zone rather than a discrete contact. In areas where the orientation of dike contacts can be ascertained, they appear to be oriented approximately orthogonal to the regional trend of the batholith contact. All metavolcanic and intrusive rocks in the vicinity of the contact show little evidence of strain and only weak (possibly magmatic flowage) fabrics are developed locally. There is also no obvious contact metamorphic aureole.

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*Summary of Field Work and Other Activities 2009,  
Ontario Geological Survey, Open File Report 6240, p.13-1 to 13-6.*

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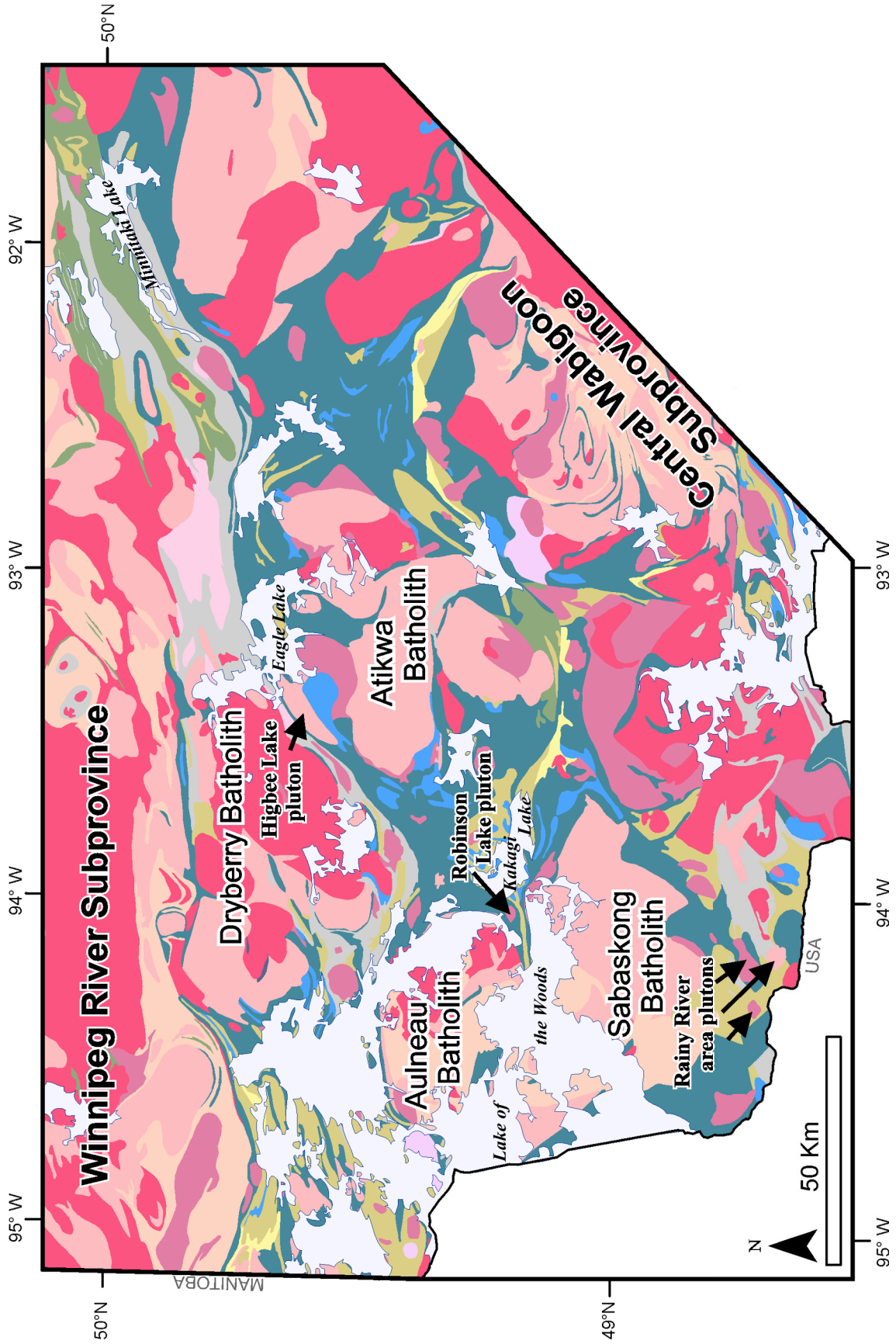


Figure 13.1. General geological map of the western Wabigoon Subprovince indicating locations of some of the features discussed in the text.

In contrast, the southeastern and eastern margin of the Aulneau batholith is characterized by a sharp, distinct contact. Metavolcanic rocks at the contact are amphibolitic. The intensity of development of a penetrative deformational fabric increases towards the contact both within the mafic metavolcanic country rocks and marginal phases of the batholith. Extremely well-developed, locally mylonitic, fabrics are associated with the immediate contact area. Felsic dikes occur in the immediate vicinity of the contact (<10 m from contact) and are of 2 distinct types (Photos 13.1a and 13.1b). One type is intensely foliated to mylonitic leuco-tonalite sheets that are approximately concordant with respect to the contact and foliation in country rocks (*see* Photo 13.1b) and are provisionally interpreted to be related to proximal, foliated phases occurring within the batholith. The second type of dike (*see* Photo 13.1a), which occurs along the southeast contact, is represented by narrow, undeformed to weakly deformed dikes of approximate quartz dioritic composition that postdate the well-developed tectonic fabric defined by amphibolite-facies metamorphic mineral assemblages. The petrogenetic affinity of this second type of dike, which provide a maximum age constraint on the timing of fabric development, will be the subject of more detailed investigations. If these dikes are related to phases occurring within the Aulneau batholith, this would indicate the fabric developed very early, whereas, if the dikes have affinity with a suite of late tectonic plutons (e.g., Robinson Lake pluton discussed below), these relationships are permissive of later development of the fabric. In the second case, localization of the dikes distally from their source near the contact reflects structural control.

The foregoing discussion suggests that the large, synvolcanic batholiths that form the core of regional structural culminations in the western Wabigoon Subprovince may have either intact primary intrusive relationships with broadly coeval, overlying metavolcanic sequences or these contacts may be highly modified by subsequent deformation. In the latter case, this may imply that the final emplacement may, in some cases, be tectonic and contact relationships may shed light on the subsequent deformational history.

## CHARACTERISTICS OF SELECTED DISCRETE PLUTONS

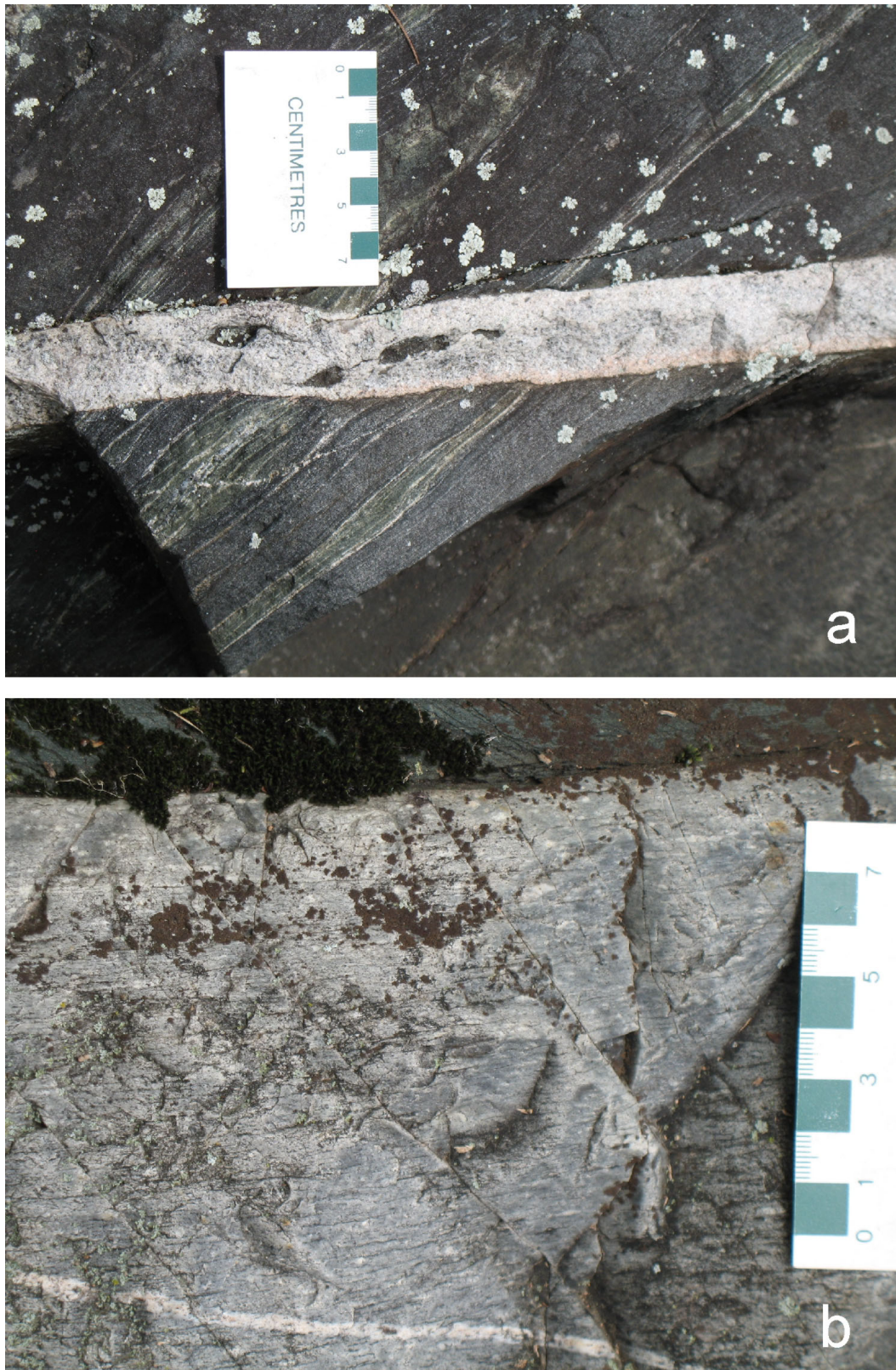
A number of discrete plutons were examined and sampled during the field season. The principal objective of this effort was sampling for subsequent petrographic, whole rock geochemical and mineral chemical analysis and, in some cases, geobarometry and geochronology. Some general field characteristics of plutons examined are summarized below.

### Robinson Lake Pluton

The Robinson Lake pluton is a small, approximately circular (~3 km diameter) intrusion occurring in a relatively narrow volcanic septum separating the Aulneau and Sabaskong batholiths and located approximately 14 km northwest of the town of Nestor Falls. The approximate mineralogical composition is biotite-hornblende granodiorite with much of the potassium feldspar occurring as large, subhedral megacrysts. Dioritic enclaves and small ultramafic clots are a widespread, but volumetrically minor, component of the granodiorite. Minor pegmatitic to aplitic granitic dikes are restricted to margin portions of the pluton.

### Higbee Lake Pluton

The Higbee Lake intrusion is located approximately 25 km south of the town of Vermilion Bay. The intrusion is elongate in a northeast direction and is in contact to the northwest with a thin septum of metavolcanic and metasedimentary rocks transected by the Wabigoon fault. A series of exposures were examined in one small portion of the pluton hosting copper mineralization (Scarp Lake property: Hinz et al. 2005). A noteworthy characteristic of the area is anomalously high ytterbium abundances in lake sediments over part of the intrusion (C. Ravnaas, personal communication, 2009; Felix 2005).



**Photo 13.1.** Photos from eastern and southeastern contact of Aulneau batholith. a) Undeformed quartz dioritic dike crosscutting well-developed fabric that is parallel to the contact of the batholith and defined by an amphibolite-grade metamorphic mineral assemblage. b) Mylonitic fabric developed within tonalite dike.

Outcrops examined are relatively leucocratic, biotite tonalite with a weakly to moderately well-developed foliation. Texture ranges from equigranular to quartz porphyritic. This intrusion likely has affinity with the synvolcanic TTG suite. More speculatively, the highly siliceous character (inferred from presence of quartz phenocrysts) and ytterbium enrichment in lake sediments suggest a possible low-aluminum TTG affinity although confirmation of this must await completion of whole rock geochemical analyses.

## Rainy River Area Plutons

A number of exposures were examined in 3 plutons lying within an area of limited outcrop exposure near the villages of Stratton and Pinewood. The plutons examined are centred approximately 2 and 8 km north of the village of Stratton and 3 km north of the village of Pinewood (Johns 1988). All plutons have only weak, possibly magmatic fabrics and are interpreted to be relatively late intrusions. They have an approximate hornblende-biotite quartz diorite bulk composition and are characterized by the presence of minor, widely distributed dioritic enclaves and rare ultramafic clots. Magnetic susceptibility is quite variable on a variety of scales. On the basis of their general characteristics, these plutons may have affinity to the late, mantle-derived (sanukitoid) suite, but geochemical data are required to confirm this.

## St. Anthony Pluton

The St. Anthony pluton is located on the eastern shore of Sturgeon Lake near the contact between the Savant–Sturgeon greenstone belt and Lewis Lake batholith and hosts the past-producing St. Anthony Mine (63 310 ounces Au and 16 341 ounces Ag) (Trowell 1983). Observations reported here are from the eastern portion of the pluton in the vicinity of the old production area. A more detailed discussion of the mineralization and setting is presented elsewhere (Ravnaas, Raoul and Wilson 2003). Further exploration of the area is currently being undertaken by Pacific Iron Ore Corporation.

The pluton is composed of biotite ± muscovite granodiorite. The origin of the muscovite is uncertain; coarse, disseminated plates comparable in size and habit to that of biotite are observed locally and may be primary, but most muscovite is associated with narrow shear zones and/or crack-seal quartz veins and is almost certainly secondary. Trowell (1983) noted that muscovite is proximal to the mineralized zone and may replace biotite. The pluton generally lacks a well-developed penetrative fabric except in the vicinity of narrow, well-foliated, north-northeast-trending, sericitic zones that host crack-seal-type quartz veins from which much of the historic gold production was derived. Within adjacent, less altered portions of the pluton, widespread irregular quartz veins suggest that these portions of the pluton underwent brittle failure during deformation. In addition to the crack-seal and irregular quartz veins, a third type of silica enrichment is represented by local isolated quartz-rich segregations within marginal portions of the pluton that are interpreted to be magmatic hydrothermal segregations.

The spatial association of gold mineralization with the St. Anthony pluton is interpreted to reflect structural control. Widespread irregular quartz veins attest to the overall more brittle character of the pluton as compared with the metavolcanic rocks. However, the presence of sericitic zones cutting the pluton parallel to the north-northeast regional stratigraphic–structural trend locally facilitated more ductile behaviour and repeated introduction of auriferous fluids during deformation leading to development of crack-seal-type veins that host most of the historic production. Sericitized portions of the pluton are reported to be K<sub>2</sub>O enriched and Na<sub>2</sub>O depleted (Trowell 1983) suggesting that potassic, auriferous magmatic hydrothermal fluids are potentially the mineralizing agent. If this interpretation is correct, identification of areas of potassic alteration by litho-geochemistry, gamma-ray spectrometry (coincident positive equivalent potassium (eq K) and equivalent potassium/thorium (eq K/Th) or equivalent uranium/thorium (eq U/Th) anomalies) and/or reflectance spectroscopy (K/Na in white mica) may prove to be an effective exploration tool, both within the immediate area and more regionally.

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# 14. Project Unit 09-003. Geology of the Bending Lake Area, Northwestern Ontario

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## LOCATION AND ACCESS

The Bending Lake area is located 30 to 40 km west of Ignace in northwestern Ontario. Parts of the area can be reached by Highway 17 and secondary Highway 622 as well as numerous logging roads. The area is characterized by subdued topography ranging from 385 to 490 m above sea level and is drained northwesterly by various tributaries of the Wabigoon River. The terrain is marked by forests of jackpine, poplar and spruce interspersed with lakes. Logging and limited tourism are the principal human activities in the area.

## REGIONAL GEOLOGIC SETTING

The Bending Lake area is situated in the western Superior Province of the Canadian Shield and is thought to be underlain by plutonic and supracrustal rocks of mainly Neoproterozoic age. The western Superior Province had been subdivided into several belt-like, easterly trending subprovinces dominated by volcano-plutonic, sedimentary or high-grade gneiss lithologies (e.g., Card and Ciesielski 1986) including the volcano-plutonic Wabigoon Subprovince. More recent work (Davis, Sutcliffe and Trowell 1988) showed that the Wabigoon Subprovince is divisible into a recycled, predominantly Mesoproterozoic Marmion Terrane and an isotopically juvenile Neoproterozoic western Wabigoon Terrane. Plate tectonic models involving the growth of the Superior Province by accretion of these various terranes at about 2.7 Ga have been strongly favoured by Percival et al. (2006).

Although geochronological analyses are not currently available, rocks of the Bending Lake area are thought to represent part of the western Wabigoon Terrane. The Bending Lake greenstone belt (referred to herein as “Bending belt”) is a southeastward-trending arm of the Kakagi Lake–Savant Lake greenstone belt, which extends west and north of the present area and marks the core of the juvenile simatic western Wabigoon Terrane (Davis, Sutcliffe and Trowell 1988). Similarly, the Raleigh Lake greenstone belt (referred to herein as “Raleigh belt”) is an extension of the Kakagi Lake–Savant Lake greenstone belt. Several tens of kilometres east of the present area, various Mesoproterozoic crustal blocks comprising the central Wabigoon or Marmion Terrane have been defined (D. Stone, unpublished data). The precise location of the boundary between these terranes and whether the boundary is largely intrusive or is a fault have proven difficult to establish by regional mapping.

## PREVIOUS GEOLOGIC MAPPING AND MINERAL EXPLORATION

The Bending Lake area represents the eastern half of the Stormy Lake map sheet (map 52 F/8) of the National Topographic Series (NTS). Areas covered by the adjoining map sheets to the east and south were recently mapped at 1:50 000 scale by Stone et al. (2007) and Stone, Hallé and Chaloux (1998).

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*Summary of Field Work and Other Activities 2009,  
Ontario Geological Survey, Open File Report 6240, p.14-1 to 14-7.*

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Satterly (1960a, 1960b) studied the Dymont area to the northwest and Kresz, Blackburn and Fraser (1982a, 1982b) mapped the Kawashegamuk (Long) Lake area to the northwest. Although Thompson (1934) mapped the Manitou–Stormy lakes area to the west, the Bending Lake area has not been formally mapped; this is the principal justification for the present survey. Felix (2006) completed a lake-sediment survey of the Upper Manitou Lake area including Bending Lake.

Although various parts of the Bending belt and the Raleigh belt have undergone sporadic prospecting (*see* Kenora District Geologist Office, assessment files for NTS areas 52F08SE and 52F08NE), the majority of mineral exploration has focussed on iron and base metals in the Bending belt. The occurrence of iron ore at Bending Lake has led to several geologic investigations of that area by mining companies including those of Jalore Mining Co. and Algoma Steel Ltd. in the 1950s to the 1970s. In 1977, Steep Rock Iron Mines Ltd. assessed mining the Bending Lake iron deposit (Kenora District Geologist Office, assessment file 52F08SE L1) and Bending Lake Iron Group Ltd. has recently compiled extensive drill-hole data on the iron deposit (A. Raoul, geologist, Bending Lake Iron Group Ltd., personal communications, 2009). Based on historic data, a resource of 249 Mt of ore grading 28% Fe is estimated for the deposit ([www.bendinglakeiron.com](http://www.bendinglakeiron.com)); this resource estimate is not compliant with National Instrument (NI) 43-101.

In the 1990s, Noranda Ltd. did extensive exploration for base metals in the south-central part of the Bending belt (Kenora District Geologist Office, assessment files, 52F08SE J1 to J7). A northwesterly trending zone of sodium depletion, garnet alteration and limited sulphide mineralization was defined and described by Lichtblau et al. (2001).

## GENERAL GEOLOGY

The Bending Lake area includes parts of the Bending Lake and Raleigh Lake greenstone belts and intervening felsic intrusions including the Revell batholith, Islet pluton and part of a biotite tonalite intrusion at Paddy Lake (Figure 14.1).

The Bending belt tapers southeastward over a distance of more than 20 km. Northwest of the present area, the Bending belt broadens and merges with the Kakagi Lake–Savant Lake greenstone belt, which is an extensive part of the western Wabigoon terrane (*see* Beakhouse, this volume, Article 12). Two narrow arms of the belt extending south and east of the present area wrap around the Islet and Revell intrusions (Stone, Hallé and Chaloux 1998; Stone et al. 2007).

A series of units comprising mafic metavolcanic rocks (referred to herein as “volcanic rocks”) with gabbro, intermediate volcanic rocks and clastic metasedimentary rocks (referred to herein as “sedimentary rocks”) make up the Bending belt. These units range up to 2 km in thickness and many extend the full length of the belt (*see* Figure 14.1). Intermediate volcanic rocks occur primarily along the northeast margin of the Bending belt and in a mass west of Bending Lake and extend west of the present area. These are fine- to medium-grained, generally grey and variously foliated rocks containing rounded fragments of volcanic material including lapilli and bombs. North of Bending Lake, intermediate volcanic rocks are intimately associated with and cut by masses and dikes of mesocratic biotite tonalite.

At least 3 major units of mafic volcanic rocks extend through the central and southern parts of the Bending belt. These are generally fine to medium grained, dark green and massive to foliated or gneissose. Variably stretched pillows are observed at many localities in larger outcrops and, elsewhere, more massive and medium- to coarse-grained phases represent either massive flows or gabbro intrusions. The southernmost mafic volcanic unit, which wraps around the Islet pluton, is distinguished from other mafic volcanic units mainly by a black colour; it may represent a distinct volcanic assemblage that extends west through Wapageisi Lake.

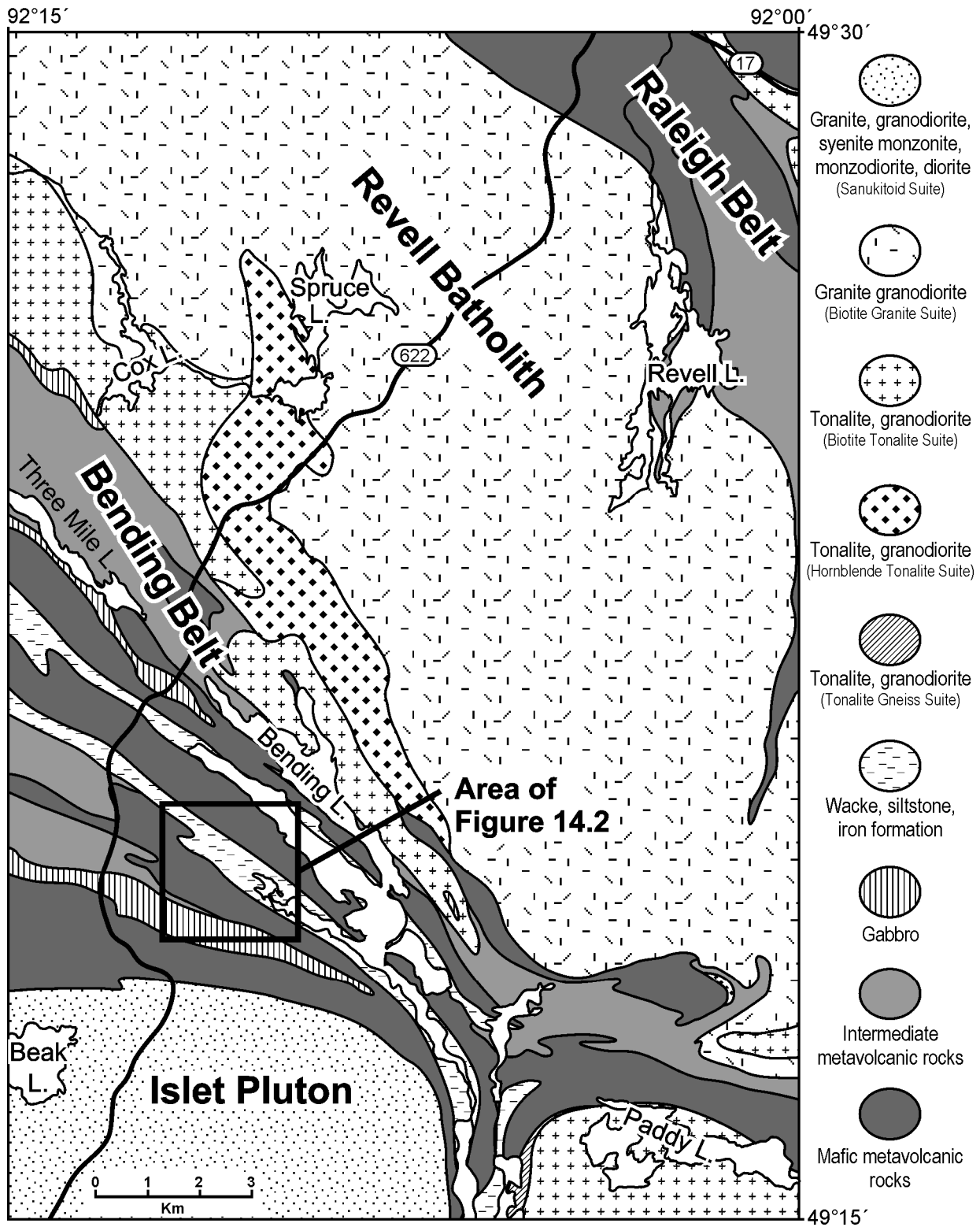
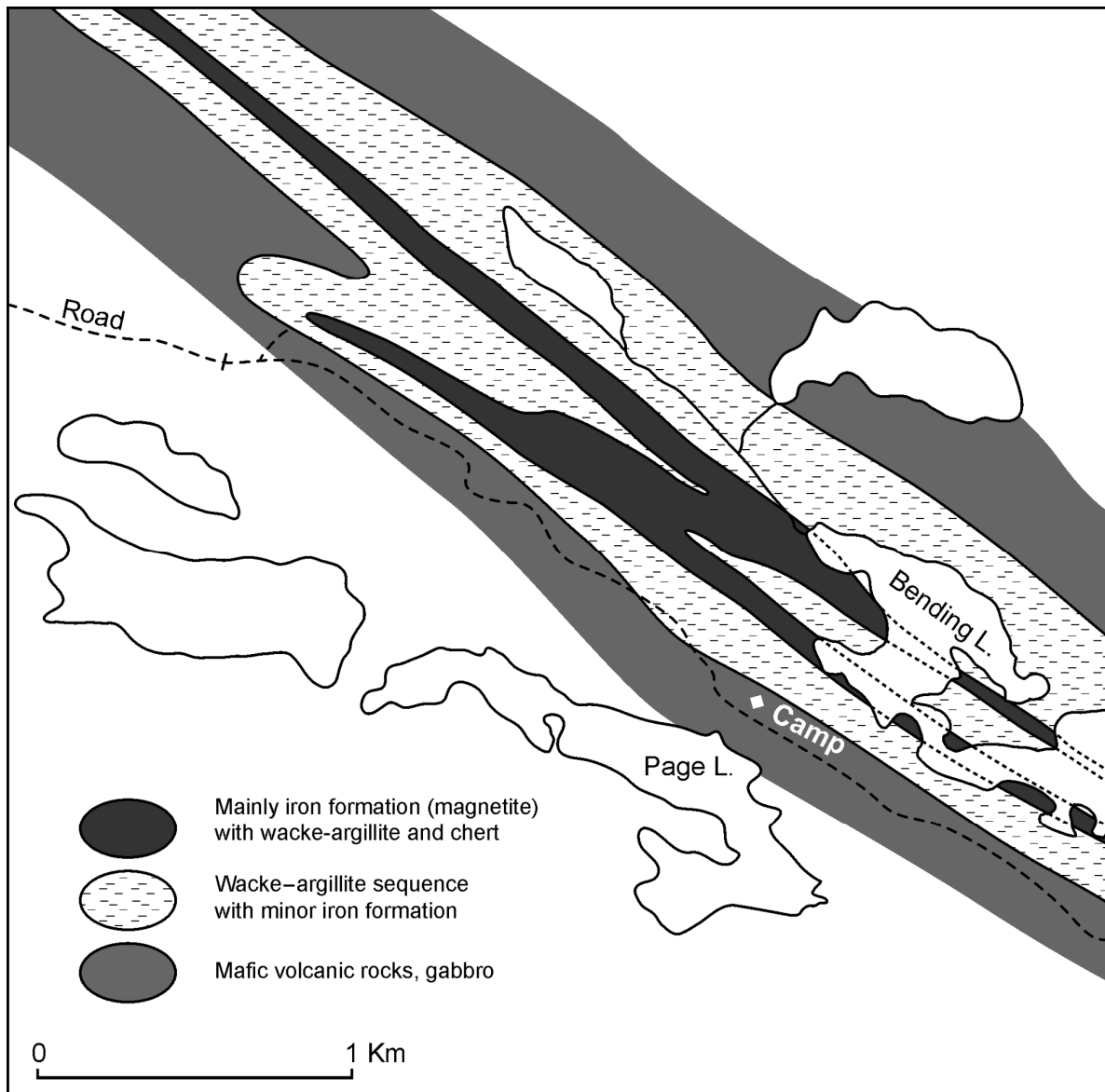


Figure 14.1. Geology of the Bending Lake area.

Two units of sedimentary rock extend southeasterly through the Bending belt. For the most part, the units are composed of well-bedded wacke and siltstone with minor conglomerate. Distinct beds of black, fine-grained magnetite with minor chert (typically several centimetres thick) are interbedded with wacke and siltstone in the southern sedimentary unit. The magnetite beds extend along or through nearly the full length of the southern sedimentary unit and produce a strong magnetic anomaly in regional aeromagnetic maps (Ontario Geological Survey 2001). Although poorly exposed, the iron formation has been explored by diamond drilling in recent decades (*see* “Previous Geologic Mapping and Mineral Exploration”) and attains its greatest thickness northwest of the southern bay of Bending Lake, where the iron formation has been tectonically thickened by an isoclinal fold (Figure 14.2).

A small segment of the Raleigh belt occurs in the northeast corner of the present area (*see* Figure 14.1). Similar to the Bending belt, the Raleigh belt represents a southeast extension of the Kakagi Lake–Savant Lake greenstone belt of the western Wabigoon Terrane. In the present area, the Raleigh belt is composed of



**Figure 14.2.** Geology of the Bending Lake iron deposit compiled from unpublished company maps provided courtesy of Bending Lake Iron Group Ltd.

units of intermediate and mafic volcanic rocks cut by biotite tonalite. The intermediate volcanic rocks are mainly medium-grained, grey and strongly foliated tuffs and breccias. A few kilometres east of the present area, the intermediate volcanic breccia has an age of 2730 Ma (D. Stone, unpublished data).

Mafic volcanic rocks of the Raleigh belt are mainly fine-grained, dark green to black pillowed lava flows. Generally, the mafic flows have less intensely developed foliation than the intermediate volcanic units and pillows tend not to be strongly stretched. These observations imply that the mafic unit could be younger than the intermediate volcanic unit. Both mafic and intermediate volcanic rocks are cut by dikes and masses of biotite tonalite near Highway 17 (*see* Figure 14.1).

Most of the Revell batholith is made up of a coarse-grained, pink massive and potassium feldspar megacrystic biotite granite to granodiorite. This is the youngest phase of the batholith, but older tonalitic phases occur as elongate units mainly along the western margin. For example, coarse-grained, grey mesocratic hornblende tonalite occurs extensively in the Spruce–Bending lakes area. This hornblende tonalite is cut by the biotite granite, but intrudes older biotite tonalite, which occurs along most of the western margin of the Revell batholith between Cox and Bending lakes. The oldest component of the batholith is generally medium-grained, foliated mesocratic biotite tonalite that intrudes intermediate volcanic rocks of the Bending belt.

The mapped part of the oval-shaped intrusion at Paddy Lake is composed of coarse-grained biotite tonalite. Strongly banded tonalitic rocks occur at the west margin of this intrusion along the Turtle River and can be either tonalite gneisses of magmatic origin or deformed arkosic sediments. High strain precludes a precise interpretation of the protolith of the banded tonalitic rocks west of Paddy Lake.

The Islet pluton is composed of coarse-grained, grey to pink and generally massive quartz-undersaturated rocks ranging compositionally from diorite through monzodiorite to monzonite. Locally, mafic phases of coarse-grained grey to black gabbro and hornblende are observed. Granodioritic to granitic units occur in marginal areas. The mafic minerals include hornblende, biotite and clinopyroxene and comprise up to 20% of the rock. The Islet pluton is interpreted to be a member of the sanukitoid suite of late intrusive rocks (D. Stone, unpublished data).

## METAMORPHISM

Mineral assemblages indicative of metamorphic grade vary substantially in the Bending belt. For example, mafic volcanic rocks at margins and in thin eastern extensions of the belt contain amphibole+plagioclase, whereas similar rocks in the thick northwestern core of the belt appear to contain assemblages of chlorite+plagioclase±epidote. Similarly, intermediate volcanic rocks contain an assemblage of biotite+plagioclase at most localities and probably chlorite+plagioclase in the northwestern core of the belt. These observations possibly indicate that margins and thin extensions of the belt have been contact metamorphosed to amphibolite facies by surrounding batholiths.

In the southern sedimentary unit, approximately in the area indicated by Figure 14.2, a mineral assemblage of staurolite+garnet+plagioclase+biotite is observed in pelitic rocks. Similarly, an assemblage of garnet+amphibole is observed in mafic volcanic rocks at scattered localities. Garnet is prevalent within a zone of several hundred metres width and extending through volcanic rocks immediately south of the southern sedimentary unit. This garnet zone has been interpreted as an alteration zone (*see* “Previous Geologic Mapping and Mineral Exploration”).

Mafic volcanic rocks within parts of the Raleigh belt appear to contain mainly amphibole and plagioclase.

## STRUCTURE

A few south-younging directions are derived from pillow shapes in mafic volcanic and graded beds in sedimentary units mainly along Highway 622 through the Bending belt. In contrast, north-younging pillows are observed at one locality in the southernmost (Wapageisi Lake) volcanic unit. These limited observations imply that the Bending belt is either folded or contains 2 or more distinct assemblages.

Apparently horizontal pillows are observed in vertical roadcuts through mafic pillow lavas at 2 localities where Highway 622 crosses the Raleigh belt. These observations imply that volcanic strata of the Raleigh belt, at least locally, have not been rotated subvertically as is the case for most Archean supracrustal strata.

A diffuse zone of high strain marked by mylonite occurs along the northeast side of the Bending belt at Bending Lake. This deformation is localized mainly in biotite tonalite and appears to represent shearing that occurred prior to intrusion of the main granitic phase of the Revell batholith. High strain also occurs at several localities within the Bending belt such as between Three Mile Lake and Bending Lake and in the Raleigh belt approximately along Highway 17. Generally poor exposure precludes accurately mapping the complete extent of these faults.

## ECONOMIC GEOLOGY

The Bending Lake area has the potential to host deposits of iron, base metals and gold. Among these, the iron mineralization at Bending Lake has had the most extensive exploration and comprises a moderate tonnage of ore with about 28% iron in the area shown by Figure 14.2.

A garnet-bearing alteration zone extends northwesterly through volcanic rocks of the Bending belt at the southern contact of the southern sedimentary unit. This garnet-bearing zone has characteristics of a metamorphosed sea-floor alteration zone such as is associated with volcanogenic massive sulphide deposits and has been studied by Lichtblau et al. (2001). Although previously explored, this alteration zone is worthy of further evaluation for base metals.

The Raleigh belt is cut by a diffuse zone of northwesterly trending deformation approximately along Highway 17. Tonalite within this zone is locally sheared, cut by quartz veins and mineralized with minor pyrite. This zone represents a largely untested gold target in the Raleigh belt. Gold and platinum group metals are potentially associated with intermediate intrusions such as the Islet pluton. Coarse-grained, grey gabbroic phases such as are found in the Drum–Osprey lakes area need to be explored for zones with trace amounts of sulphides having associated gold and platinum group metals.

## ACKNOWLEDGMENTS

Michael Lange, Barbara Hellebrandt, Kathleen McDonald and Robin Westland assisted with field work. I thank Allen Raoul of Bending Lake Iron Group for providing unpublished data. The manuscript benefited from comments by Jack Parker, Tom Brown and Monica Gaiswinkler Easton.

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# 15. Project Unit 09-007. Field Investigations in the Lumby Lake Greenstone Belt, Northwestern Ontario: New Insights into the Geology, Structure and Economic Potential

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## INTRODUCTION

The Lumby Lake greenstone belt is located 40 km northeast of Atikokan in northwestern Ontario (Figure 15.1A). A new, detailed airborne magnetic and electromagnetic geophysical survey was flown over the Finlayson–Lumby lakes area in 2009 (Ontario Geological Survey 2009) as part of the Atikokan Mineral Development Initiative (AMDI). The Ontario Geological Survey subsequently conducted a 1:20 000 scale bedrock mapping project in the Lumby Lake greenstone belt with the support of the Atikokan Mineral Development Initiative with the goals of

1. updating the geological and structural interpretation of the greenstone belt
2. correlating the new regional geophysics with the bedrock mapping
3. integrating new geochemical and geochronological data into existing databases
4. stimulating mineral exploration within the Lumby Lake greenstone belt

This article provides a summary of the updated structure, stratigraphy and economic potential of the Lumby Lake greenstone belt and a new interpretation for its formation. The stratigraphy and the structural geology have been revised and geophysical trends from the new survey are being used to aid in the new interpretation. Geochemical, geochronological and assay samples were collected from across the belt and are currently being analyzed.

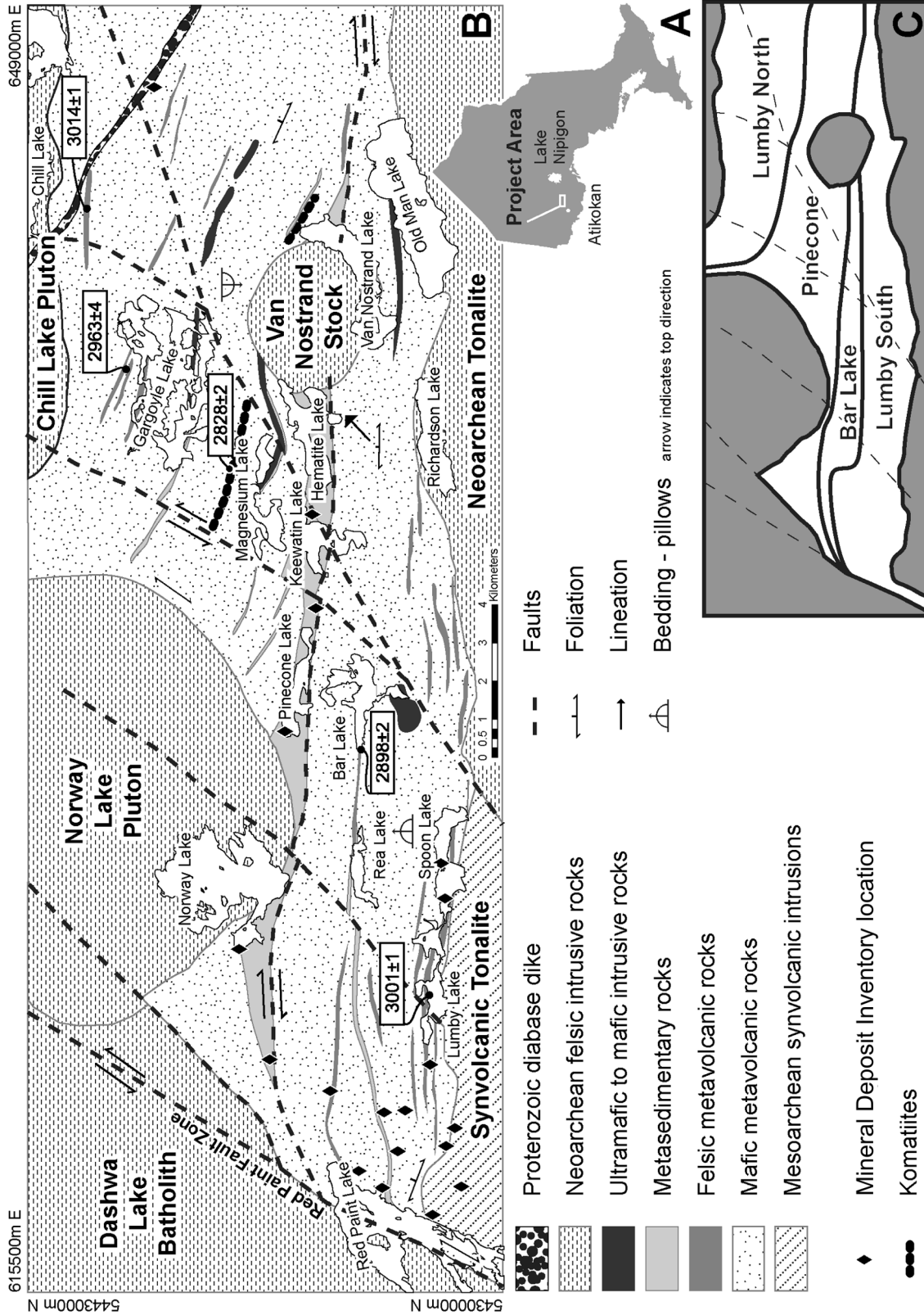
## REGIONAL GEOLOGY

The Mesoproterozoic Lumby Lake greenstone belt is located within the Marmion Terrane of the Wabigoon Subprovince (Tomlinson et al. 2004) and is surrounded by the Steep Rock and Finlayson greenstone belts. Komatiites within the Lumby Lake greenstone belt are related to komatiites within the Steep Rock greenstone belt (Tomlinson et al. 1999), which was determined in part by geochemistry, and the Finlayson greenstone belt, which is interpreted to be the fault-offset continuation of the Lumby Lake greenstone belt (Fralick and King 1996; Wyman and Hollings 1998). An attempt to correlate the stratigraphy of the belt and the metasedimentary rocks within the Lumby Lake and adjacent greenstone belts was recently completed by Fralick, Hollings and King (2008).

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*Summary of Field Work and Other Activities 2009,  
Ontario Geological Survey, Open File Report 6240, p.15-1 to 15-15.*

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The first significant regional bedrock mapping of the Lumby Lake greenstone belt was by Woolverton (1960) who documented mostly mafic metavolcanic rocks, lesser metasedimentary and plutonic rocks as well as the major structures within the belt. Woolverton (1960) interpreted a belt-scale, east-trending syncline based on the reversal of younging directions in the mafic metavolcanic rocks. Jackson (1985a, 1985b) further demonstrated that the Lumby Lake greenstone belt was formed by bimodal mafic and felsic volcanism and supported Woolverton's (1960) synclinal interpretation. Mapping by Jackson (1985a, 1985b, 1985c) and Jackson and Chevalier (1985) also demonstrated the presence of ultramafic metavolcanic rocks and were a strong incentive for base and precious metal exploration. Further work by Tomlinson et al. (1999, 2003), Davis and Jackson (1988) and Hollings and Wyman (1999) demonstrated that the Lumby Lake greenstone belt (*circa* 3014 to 2830 Ma) is a volcano-sedimentary belt that unconformably overlies the Marmion batholith (*circa* 3003 to 3001 Ma) to the south; is in fault contact with the Dashwa Lake batholith (*circa* 2677 Ma: Kamineni, Stone and Peterman 1990) to the west; and is bounded by Neoproterozoic intrusive rocks to the north and east. The mafic and ultramafic metavolcanic rocks, based on  $\epsilon_{\text{Nd}}$  data and inherited zircon studies, are interpreted to have erupted through the Marmion batholith (Hollings and Wyman 1999). Mafic dikes, interpreted to be feeder dikes to the overlying mafic flows, have been reported within the Marmion batholith (Stone, Kamineni and Jackson 1992).

The Lumby Lake greenstone belt was originally interpreted to comprise 4 tectonostratigraphic assemblages based on the lithology, geochemistry, airborne electromagnetic data and geochronology of the metavolcanic rocks (Tomlinson et al. 2003): the Lumby North, Lumby South, Bar Lake and Pinecone assemblages. The Lumby South and Bar Lake assemblages face to the north and range from mafic metavolcanic to felsic metavolcanic rocks that unconformably overlie the Marmion batholith. Age determinations for a felsic tuff at the base of the Lumby South assemblage range from *circa* 2998 to 3000 Ma with the oldest age determination at *circa* 3001 Ma (Davis and Jackson 1988; Tomlinson et al. 2003), which is interpreted to represent the age of initial volcanism in the southern portion of belt. The Bar Lake felsic tuff lies at the base of the Bar Lake assemblage and has an age of *circa* 2898 Ma (Tomlinson et al. 2003).

In contrast to the Lumby South and Bar Lake assemblages, the Lumby North and Pinecone assemblages both face to the south. The Lumby North assemblage is a sequence of mafic and felsic metavolcanic rocks. A tuffaceous unit at the base of the Lumby North assemblage has an age of *circa* 3014 Ma (Tomlinson et al. 2003), representing the oldest age within the greenstone belt. Near the centre of the Lumby North assemblage, the Tiny Lake tuff yielded an age of *circa* 2963 Ma (Tomlinson et al. 2003). The Pinecone assemblage is a sequence of mafic metavolcanic rocks with local occurrences of komatiite, sulphide and oxide-facies iron formation, and a metasedimentary sequence of wacke, conglomerate, marble and iron formation near the trace of the regional syncline. Work by Tomlinson et al. (1999) on the komatiitic rocks in the Pinecone assemblage suggests that the transition from tholeiitic to komatiitic volcanism represents melting of the upper mantle by an ascending mantle plume, followed by direct contribution from different parts of the plume to form the komatiitic magmas. Based on litho-geochemistry and Sm–Nd isotopic evidence, Wyman and Hollings (1998) and Hollings and Wyman (1999) also proposed that the komatiites are the result of a mantle plume, but suggested that the calc-alkaline nature of the intermediate and felsic metavolcanic rocks is indicative of an Archean subduction environment. Wyman and Hollings (1998) and Hollings and Wyman (1999) further suggest that the Lumby Lake greenstone belt is the result of subduction of plume-modified oceanic spreading centres and potentially mantle plume impingement on the subduction zone. However, these studies are based on the synclinal structural model of Woolverton (1960), which was questioned by Tomlinson et al. (1999).

## STRATIGRAPHY

Four tectonostratigraphic assemblages were initially proposed by Tomlinson et al. (1999) based on the lithogeochemistry and geochronology of the Lumby Lake greenstone belt. However, mapping during the 2009 field season and new aeromagnetic geophysical data suggest that the 4 tectonostratigraphic assemblages should be reclassified as depositional sequences which form 2 tectonostratigraphic assemblages: one in the north and one in the south. An assemblage, as used within the Superior Province, is defined as metasedimentary or metavolcanic rocks that are bounded by faults, unconformities or intrusions and were deposited in a similar setting in a discrete time interval with similar structural, metamorphic, geophysical and geochemical characteristics (Ontario Geological Survey 1992).

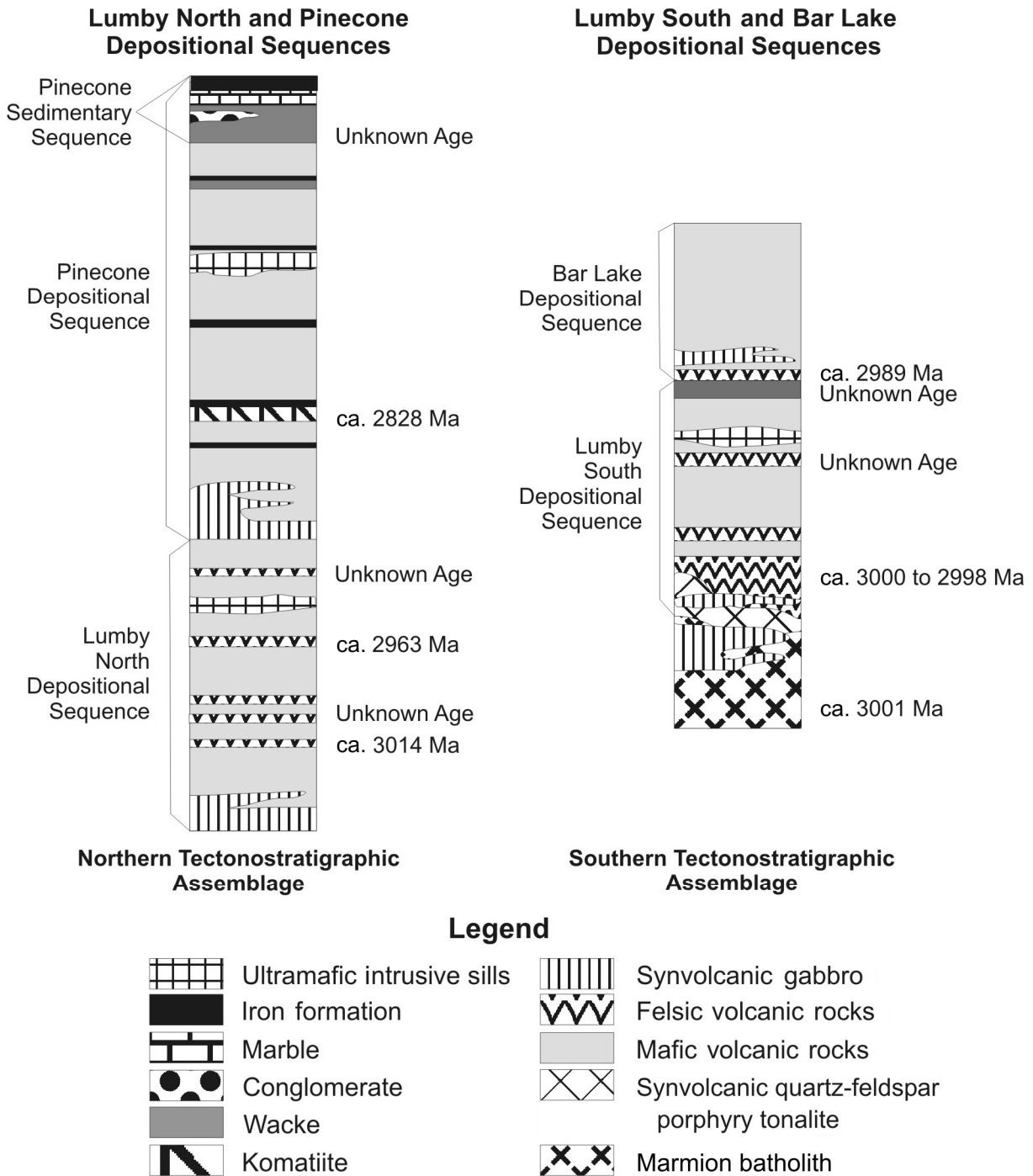
Depositional sequences are defined as conformable units of genetically related rocks separated from other sequences by unconformities (Ontario Geological Survey 1992), which accurately describes the packages of rocks within the Lumby Lake greenstone belt. In this article, the assemblage names from Tomlinson et al. (2003) are maintained, but are reclassified as depositional sequences. The Lumby South and Bar Lake depositional sequences comprise the southern tectonostratigraphic assemblage and the Lumby North and Pinecone depositional sequence comprise the northern tectonostratigraphic assemblage. A simplified preliminary geologic map is hereby presented (Figure 15.1B) as well as a map showing the depositional sequence boundaries (Figure 15.1C). A summary of the northern and southern depositional sequences can be found in 2 stratigraphic columns (Figure 15.2).

### Lumby South and Bar Lake Depositional Sequences

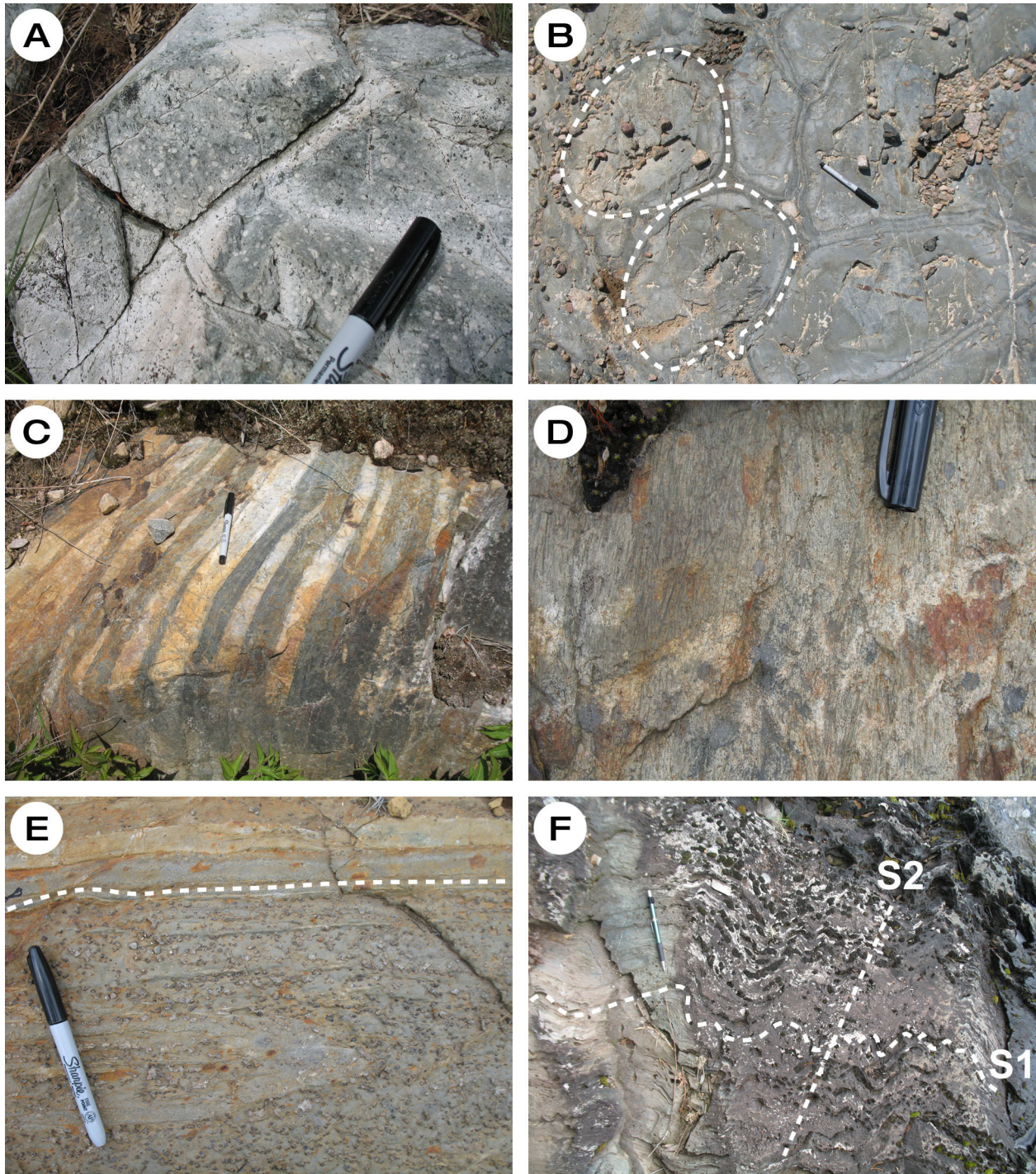
The north-facing Lumby South depositional sequence unconformably overlies the Marmion batholith (*circa* 3003 Ma; Davis and Jackson 1988) and, together with the Bar Lake depositional sequence, comprise the southern tectonostratigraphic assemblage (*see* Figure 15.1C). The Lumby South depositional sequence consists predominantly of mafic metavolcanic flows, interlayered with felsic pyroclastic rocks and is capped by quartz arenite. South of the Lumby Lake and Spoon Lake area and westward toward the Red Paint fault zone, an intrusive synvolcanic quartz-feldspar-porphyrific tonalite stratigraphically above the Marmion batholith is morphologically similar to the felsic quartz-feldspar-phyric tuffs that conformably overlie the tonalite. This intrusion is interpreted to be the intrusive equivalent to the overlying felsic tuffs. The tonalite is intruded by synvolcanic gabbroic units that make up much of the base of the greenstone belt. In the eastern portion of the map area, a much larger volume of gabbro was mapped than what was originally reported by Jackson (1985a, 1985b, 1985c) and Jackson and Chevalier (1985). The gabbro commonly intrudes the felsic tuffs along bedding planes, resulting in repetitive successions of interbedded felsic tuff and gabbro.

The felsic tuff at the base of the greenstone belt contains quartz phenocrysts  $\pm$  plagioclase phenocrysts  $\pm$  lapilli. They are thinly bedded to massive and welded with weak to strong chlorite and/or sericite alteration. The quartz phenocrysts range from 0.3 to 1 cm in size, are subhedral to euhedral and locally make up to 15% of the tuffaceous units (Photo 15.1A). Lapilli are found locally, and commonly occur in specific horizons that can be traced along strike. Plagioclase phenocrysts are rare within the tuff and, where present, are 1 to 4 mm and subhedral. These felsic tuffs are generally 1 to 5 m thick and often concentrate the dextral shearing along the margin of the greenstone belt; furthermore, the felsic tuffs commonly contain copper-lead-zinc-silver mineralization. The Lumby South depositional sequence is dominated by massive mafic metavolcanic flows that conformably overlie the felsic tuffaceous units at the base of the greenstone belt. The mafic volcanic rocks make up repetitive successions of synvolcanic gabbros overlain by massive basalt, pillowed basalt, pillow and flow-top breccia with varying amounts of hyaloclastite in the pillow selvages and hyaloclastite breccia. Amygdules occur locally throughout the Lumby South depositional sequence and are often irregular and filled with plagioclase or quartz. Pillow selvages are 0.8 to 1.0 cm thick on average, whereas pillows are 20 to 50 cm wide with ovoid to bulbous

shapes. Many of the pillows are “eyebrow-shaped” and drape over each other. In the Lumby and Spoon lakes area, felsic tuffs are interbedded with thin mafic metavolcanic flows that are commonly massive and may contain amygdules that are 1 to 2 cm in size. A quartz arenite is located near the top of this depositional sequence and can be traced in outcrop from the Red Paint fault zone to Rea Lake (see Figure 15.1B). The quartz arenite consists of medium- to coarse-grained quartz sand with 2 to 10 cm long, subrounded quartz clasts.



**Figure 15.2.** Stratigraphic columns for the northern and southern tectonostratigraphic assemblages. Plotted ages are from Tomlinson et al. (2003).



**Photo 15.1.** Select photos from the Lumby Lake greenstone belt. A) Fine-grained felsic tuff of the Lumby South depositional sequence. Medium- to coarse-grained quartz phenocrysts are characteristic of this rock unit. Pen for scale. B) Mafic pillowed flow in the Lumby North depositional sequence. Two pillow selvages are outlined in white. Pen for scale. C) Banded oxide-facies iron formation of the Pinecone depositional sequence. Pen for scale. D) Recrystallized spinifex texture in an ultramafic volcanic flow of the Pinecone depositional sequence. Pen for scale. E) Fine-grained graded wacke of the Pinecone depositional sequence. Coarse-grained metamorphic garnets overgrow the primary bedding. Bedding is highlighted in white. Pen for scale. F) Folded mafic volcanic flow of the Lumby South depositional sequence. The strong, folded  $S_1$  foliation is defining  $F_2$  folds near Red Paint Lake. Pencil for scale.

The boundary relationship between the Lumby South and Bar Lake depositional sequences is not clear and there is some question whether the two sequences actually exist. Further geochemical and geochronological work needs to be completed to resolve this issue. At Rea Lake, the quartz arenite is directly overlain by the Bar Lake felsic tuff (*circa* 2898 Ma; Tomlinson et al. 2003); however, the quartz arenite is not directly overlain by the tuff in the western portion of the greenstone belt. Also, a continuous sequence of mafic metavolcanic flows is situated in the eastern portion of the belt, north of Jefferson Lake, which suggests the absence of a distinct depositional sequence boundary. If indeed the boundary does exist, it is likely represented by the base of the Bar Lake tuff which pinches out to the east of Bar Lake. This tuff is quartz porphyritic with 1 to 2 mm subhedral quartz phenocrysts as well as 2 to 4 mm plagioclase-rich lapilli. Conformably overlying the Bar Lake tuff are mafic metavolcanic rocks that range from synvolcanic gabbro to massive or pillowed mafic metavolcanic flows to thin flow-top breccias. Gabbro dikes intrude the mafic metavolcanic rocks and are interpreted to be feeder dikes to the stratigraphically higher mafic metavolcanic rocks. Hyaloclastite breccia and hyaloclastite occur locally. Thin vesiculated flows occur at the top of the Bar Lake depositional sequence.

## Lumby North and Pinecone Depositional Sequences

The Lumby North and Pinecone depositional sequences comprise the northern tectonostratigraphic assemblage of the Lumby Lake greenstone belt and are south-facing, conformable successions of mafic metavolcanic rocks with intercalated felsic tuffs and chemical and clastic metasedimentary rocks. This assemblage is separated from the southern assemblage by a fault between the Pinecone metasedimentary rocks and the top of the Bar Lake depositional sequence, where the original synclinal trace of Woolverton (1960) was located.

At the base of the Lumby North depositional sequence are mafic metavolcanic rocks with well-formed, bulbous pillows, varioles accumulated at the margins of the pillows and 2 to 3 mm wide degassing pipes perpendicular to the pillow margin. The mafic metavolcanic pillows range in diameter from 10 cm to 1.5 m megapillows with 0.8 to 3 cm selvages (Photo 15.1B). Abundant hyaloclastite is found within pillow selvages in this depositional sequence. Rare double pillow selvages are found and may suggest that the pillows were near the surface when forming. Sequences of 10 to 100 m thick mafic massive to pillowed to breccia sequences can be traced where exposure is good. Felsic tuffs are intercalated with the mafic metavolcanic flows throughout the Lumby North depositional sequence, but are morphologically different from those of the Lumby South depositional sequence. These felsic tuffs are thinly bedded and contain 5 to 10% quartz phenocrysts that are 1 to 3 mm in size. Lapilli-size clasts and plagioclase phenocrysts are rare.

The boundary between the Lumby North and Pinecone depositional sequences denotes a shift in depositional setting within the belt from bimodal volcanism toward a basinal setting where mafic and ultramafic metavolcanic rocks and clastic and chemical metasedimentary rocks were deposited. The boundary between the Lumby North and Pinecone depositional sequences is located along the southern side of Gargoyle Lake. At the base of the Pinecone sequence is a massive synvolcanic gabbro conformably overlain by massive to pillowed mafic metavolcanic rocks with local flow-top breccias. The pillows are typically bulbous, locally eyebrow-shaped, and range in diameter from 20 cm to 1 m. Vesicles occur within the mafic metavolcanic rocks only near the top of the Pinecone depositional sequence. Banded oxide- and sulphide-facies iron formation are intercalated within the mafic metavolcanic flow units and are locally found as long thin, irregularly shaped lenses and pods within synvolcanic gabbroic sills. Banded oxide-facies iron formations are typically 1 to 2 m thick and contain interlayered chert and muddy magnetite layers (Photo 15.1C). The chert layers are up to 15 cm thick, whereas the magnetite layers range from 2 to 10 cm. Chert is rarely preserved, being almost entirely recrystallized to fine-grained quartz. The sulphide-facies iron formation is very fine-grained argillitic mud with up to 30%

pyrrhotite and pyrite. Rare komatiitic metavolcanic flows are found in the Pinecone depositional sequence. South of Gargoyle Lake, komatiite flows are observed ranging from 1 to 5 m thick with well-developed progressions of basal cumulate to randomly oriented spinifex to long spinifex near the top. The long spinifex are up to 10 cm long and are altered to serpentine (Photo 15.1D). Flow-top breccias are found at the top of the individual komatiitic flows. Interlayered with the komatiitic rocks is a thin sulphide-facies iron formation that exhibits a thermal erosion contact with the overlying flow. The komatiite located east of the Van Nostrand stock is volcanoclastic. It has subrounded clasts ranging from 1 to 15 cm in length and the groundmass is composed of fine-grained material of similar composition to the clasts.

In the upper central portion of the Pinecone depositional sequence, 10 to 15 m wide packages of bedded wacke are observed with iron formation within the mafic metavolcanic rocks. This is interpreted to represent the beginning of basinal sediment deposition. The uppermost portion of the Pinecone depositional sequence is composed of chemical and clastic metasedimentary rocks. The dominant rock type is wacke that exhibits graded bedding ranging from sand to silty mud with beds between 2 and 15 cm thick with the silty portions being generally thinner than the sandy portions of the beds (Photo 15.1E). Garnet and cordierite occur locally within the wacke as porphyroblasts. Clastic iron formation is found locally across the greenstone belt and at different levels in the strata. It commonly consists of sandstone that is weakly to moderately magnetic, with 2 to 8% pyrite  $\pm$  pyrrhotite and gossan staining on weathered surfaces. A dominantly clast-supported conglomerate with a fine-grained chloritic sandy matrix is found as a unit within the wacke. Clast size ranges from 0.5 to 30 cm long. The clast composition is dominantly mafic and felsic metavolcanic rock with lesser iron formation, gabbro and chert. Marble and iron formation overlie the clastic metasedimentary rocks. The marble contains decimetre-scale calcite beds, capped by thin calcareous mud beds. This unit varies along strike and can also appear as muddy calcareous siltstone with thin calcite beds. The oxide-facies chemical iron formation ranges in thickness from 2 to 10 cm thick beds. It is morphologically very similar to the stratigraphically lower banded iron formations, but with thicker chert beds than magnetite beds.

The sedimentary package changes laterally from west to east along strike. In the west, the full Pinecone sedimentary sequence is exposed and is folded. There are fewer carbonate rocks and no exposures of the conglomerate toward the east. On the eastern side of the greenstone belt, the graded wackes become fine-grained, bedded to massive sandstones with interbedded clastic and chemical iron formation.

## **INTRUSIVE ROCKS**

### **Mesoarchean Felsic Intrusive Rocks**

There are several different ages and affinities of intrusive rocks within the Lumby Lake map area. The Marmion batholith (*circa* 3003 Ma: Davis and Jackson 1988) acts as basement to the greenstone belt and dips very shallowly northward, accounting for the low aeromagnetic geophysical signature at the base of the greenstone belt. It is a medium-grained, biotite-bearing granodiorite gneiss. This was only observed in one locale as the base of the greenstone belt is heavily intruded by gabbro and tonalite. A synvolcanic quartz-feldspar porphyritic tonalite is situated immediately north of the Marmion batholith and is interpreted to be the intrusive equivalent of the felsic tuff at the base of the Lumby South depositional sequence. Plagioclase and quartz phenocrysts are up to 1 cm in size and range in abundance throughout the intrusion. The intrusion is always medium to coarse grained and inequigranular, and does not contain mafic minerals except for local chlorite, which is interpreted to be an alteration mineral that may have developed during shearing along the base of the greenstone belt. This synvolcanic tonalite is found only along the base of the western side of the greenstone belt.

## Mesoarchean Mafic to Ultramafic Rocks

Other Mesoarchean intrusions include synvolcanic gabbros to melanogabbros within the greenstone belt. These gabbros are frequently located at the base of massive to pillowed successions of mafic metavolcanic flows as sills or possible lava ponds and, locally, as feeder dikes to the mafic metavolcanic rocks higher in the stratigraphic succession. These gabbroic rocks are typically medium grained, containing hornblende, plagioclase, amphiboles and chlorite. The magnetism of the synvolcanic gabbroic rocks is always low, in contrast to the later ultramafic intrusions. The age of these ultramafic intrusions is unknown, but they may be synvolcanic with the komatiite flows. These intrusions occur dominantly as sills within the North and South Lumby depositional sequences and infrequently as mafic to ultramafic stocks. They are medium grained and equigranular, and contain magnetite  $\pm$  amphibole  $\pm$  pyroxene  $\pm$  serpentine  $\pm$  asbestos. There are locally gabbroic phases of this unit that grade into hornblendites and peridotites and are composed of medium- to coarse-grained hornblende with varying amounts of plagioclase. These gabbros commonly occur on the margins of the ultramafic intrusions and contain varying amounts of magnetite. Two mafic to ultramafic stocks are found within the greenstone belt, one to the west of the Norway Lake pluton and one south of Bar Lake. These stocks are coarse-grained, magnetic melanogabbro to hornblendites.

## Neoarchean Felsic Intrusive Rocks

Late intrusions in the belt have not had ages determined, but are interpreted to be syntectonic to posttectonic. These include an unnamed tonalite that underlies the southeastern portion of the greenstone belt, the Chill Lake pluton, the Dashwa Lake batholith, the Norway Lake pluton and the Van Nostrand stock. The first intrusion is a tonalite beneath the southeastern portion of the belt that was interpreted previously (Jackson 1985a, 1985b) to be part of the Mesoarchean synvolcanic tonalite beneath Lumby and Spoon Lakes. Dikes of this tonalite, however, occur within the volcanic rocks at Old Man Lake indicating that it is a later intrusion. It is medium grained, equigranular, strongly foliated, contains 15 to 20% biotite and is strongly altered by chlorite and local sericite. It is interpreted to be the oldest of the syntectonic to posttectonic intrusions. The Chill Lake pluton in the northeast portion of the belt is a medium- to coarse-grained, equigranular quartz monzonite with biotite and 3 to 4 mm long hornblende laths and local potassium feldspar stringers. Dikes from this pluton crosscut the surrounding metavolcanic rocks. A strong contact strain aureole is associated with this pluton, which is observed by the warping of the foliation away from the penetrative fabric, steeper lineations, and evidence for vertical stretching as the pluton intruded and compressed the surrounding metavolcanic rocks. The Dashwa Lake batholith (*circa* 2677 Ma: Kamineni, Stone and Peterman 1990) is a medium- to coarse-grained tonalite to granodiorite that contains quartz, plagioclase, varying amounts of alkali feldspar, and hornblende. A volumetrically minor, and possibly earlier phase, medium-grained diorite is traced locally within the pluton and contains hornblende and plagioclase.

The Norway Lake pluton ranges in composition from diorite to quartz diorite, monzonite to quartz monzonite, syenogranite, and granodiorite. It is medium to coarse grained, inequigranular and contains hornblende and magnetite. The intermediate phases along the margins of the pluton are the oldest and are crosscut by syenite and monzonite dikes. This intrusion is responsible for a contact metamorphic aureole within the sedimentary and mafic metavolcanic rocks and causes a deflection of the main foliation near the margins of the pluton. It is interpreted to have intruded during late D<sub>2</sub> deformation. The Van Nostrand stock is a late, posttectonic intrusion in the centre of the Lumby Lake greenstone belt. It is composed of 2 distinct phases: a syenite to monzonite around the edges of the pluton, and a potassium feldspar porphyritic granodiorite in the central portion of the pluton. Both phases contain biotite, but locally hornblende is found and magnetite is rare. Both the Norway Lake pluton and Van Nostrand stock have similarities to sanukitoid intrusions, but further geochemical data are needed to confirm this.

**Table 15.1.** Summary of structural features and interpretation of deformational events within the Lumby Lake greenstone belt.

<b>Event</b>	<b>Foliation</b>	<b>Lineation</b>	<b>Faults</b>	<b>Folds</b>
D <sub>3</sub>	S <sub>3</sub> - spaced, north-striking fracture foliation	not recognized	not recognized	F <sub>3</sub> - Z-shaped asymmetric folds. Axial plane strikes north
D <sub>2</sub>	S <sub>2</sub> - spaced, northeast-striking foliation	L <sub>2</sub> - moderately plunging northwest-trending elongation lineation	D <sub>2</sub> - northeast-striking sinistral and east-striking dextral oblique slip faults	F <sub>2</sub> - Z- and M-shaped folds. Axial plane strikes northeast
D <sub>1</sub>	S <sub>1</sub> - continuously developed, east-striking, chloritic foliation	L <sub>1</sub> - steeply plunging northeast-trending stretching lineation	D <sub>1</sub> - east-striking faults	not recognized

## STRUCTURE AND METAMORPHISM

### Structural Geology

Three generations of deformation are summarized in Table 15.1 for the Lumby Lake greenstone belt. Two regional foliations and one local foliation overprint the metavolcanic, metasedimentary and plutonic rocks. The oldest and dominant foliation (S<sub>1</sub>) is a steeply dipping, penetrative fabric, striking east and dipping commonly to the north. In mafic metavolcanic rocks, it is a continuously developed foliation that is defined by chlorite, actinolite, sericite, biotite and flattened pillow selvages. The intensity of the foliation ranges from weak to strong and becomes subparallel to shear zone margins. Between the Norway Lake and Chill Lake plutons, the orientation of the S<sub>1</sub> foliation bends into a north-northwest-trend as a result of the strain imposed by the intruding plutons. The penetrative foliation (S<sub>2</sub>) is a north-northeast-trending, thinly spaced, brittle–ductile fabric that is oriented counterclockwise to S<sub>1</sub>. In mafic metavolcanic and metasedimentary rocks, the foliation spacing ranges from 0.5 to 2 cm and, in felsic metavolcanic rocks, from 1 to 10 cm. The S<sub>2</sub> foliation is locally expressed as a crenulation of the D<sub>1</sub> east-striking foliation in areas of less intense foliation or shearing. The S<sub>2</sub> foliation is generally weakly to moderately developed, but becomes progressively more intense toward the Red Paint fault zone. The youngest foliation (S<sub>3</sub>) is restricted in distribution and overprints both of the older foliations. It is a weak, spaced, fracture foliation that trends north with a subvertical dip and is frequently filled in by quartz veins.

Two lineations are recognized in the Lumby Lake greenstone belt. The L<sub>1</sub> lineation is a weakly to strongly developed stretching lineation that trends northeast to east along the S<sub>1</sub> plane and plunges steeply. It tends to mimic the strength of the foliation and is particularly well developed in east-trending shear zones. It is defined by chlorite, quartz, elongated volcanic and sedimentary clasts and pillow selvages in mafic metavolcanic rocks. A local crenulation lineation (L<sub>2</sub>), restricted to the Red Paint Lake area, overprints and realigns the L<sub>1</sub> lineation. The L<sub>2</sub> lineation plunges moderately to steeply to the northwest, and is largely restricted to northeast- and east-trending shear zones although it is locally observed in less-deformed rock units.

Two generations of ductile faults are recognized. The first set of ductile faults is S<sub>1</sub> parallel and exhibits dextral shear of unknown displacement. These shear zones are defined by the intensification and chloritization of the S<sub>1</sub> foliation and range in width up to at least 50 m. The largest of these shear zones extends along the length of the map area at the boundary between the Bar Lake and Pinecone depositional sequences and is interpreted to be a major tectonic break between the northern and southern tectonostratigraphic assemblages. This large fault shows evidence for being a D<sub>1</sub> thrust fault, but, despite

a strong stretching lineation, fault kinematic indicators are rare. Those that do exist include folded quartz veins and shear bands, which suggest north-side-up thrust faulting. The base of the greenstone belt was also sheared during this faulting event, which is evident from deformation in felsic tuffs. Subsequent drag folds overprint the main shear fabric of these faults. The timing of dextral shearing along the fault is unknown relative to the D<sub>2</sub> faults.

The D<sub>2</sub> faults trend northeast and are characterized by a lack of kinematic indicators and an intensification and chloritization of the S<sub>2</sub> foliation, which is parallel to the fault margins. They include the Red Paint fault zone (RPFZ) and the numerous splays and corresponding faults that extend from the RPFZ. The RPFZ is a 600 m wide zone of intensely foliated mafic metavolcanic rocks, bounded to the west by the relatively undeformed Dashwa Lake batholith. The smaller D<sub>2</sub> splay and corresponding faults are not as wide, but are associated with a similar intensification of foliation. The L<sub>2</sub> lineation plunges steeply along the fault planes, suggesting strike-slip to oblique-slip displacement. The counterclockwise rotation of rock units and D<sub>1</sub> faults into the RPFZ, plus aeromagnetic patterns, show that the northeast-trending faults have undergone sinistral displacement.

Folding is rare in the Lumby Lake greenstone belt and 2 folding events are recognized (Photo 15.1F). The older generation of F<sub>2</sub> folds consist of M- and Z-shaped cylindrical, open folds with an amplitude and wavelength of 2 to 5 cm, uniform layer thickness, a well-developed S<sub>2</sub> axial planar foliation, and a fold hinge plunging subparallel to the L<sub>1</sub> stretching lineation. The F<sub>2</sub> folds are defined by the folded S<sub>1</sub> fabric in D<sub>1</sub> faults and fold symmetry is spatially related to the RPFZ. The M-shaped folds dominate adjacent to the RPFZ (where the D<sub>1</sub> faults are oriented normal to the RPFZ), whereas Z-shaped folds dominate further to the east (where the D<sub>1</sub> faults are oriented clockwise to the RPFZ). These folds are interpreted to have formed synchronously with the RPFZ, suggesting dextral fault reactivation of D<sub>1</sub> faults during D<sub>2</sub>. A younger F<sub>3</sub> fold generation affects the S<sub>2</sub> fabric. This S<sub>2</sub> foliation is locally Z-folded within the RPFZ. These gentle F<sub>3</sub> folds have uniform layer thickness and the north-trending S<sub>3</sub> is parallel to the fold axial plane.

## Metamorphism

The rocks within the Lumby Lake greenstone belt are metamorphosed to greenschist-facies metamorphism with local areas of upper greenschist to lower amphibolite facies. Metamorphic minerals associated with the greenschist metamorphism include chlorite with varying amounts of actinolite, biotite and epidote. In the felsic metavolcanic rocks at the base of the greenstone belt, chloritoid is present locally, which may be the result of synvolcanic alteration and not a product of metamorphism. A contact metamorphic aureole around the Norway Lake pluton produced garnet ± cordierite in the metasedimentary rocks and hornblende in the mafic metavolcanic rocks. There is also an inferred hornfels metamorphism associated with the Norway Lake pluton that formed magnetite within the mafic metavolcanic rocks surrounding the pluton.

## ALTERATION AND MINERALIZATION

In the Lumby Lake greenstone belt, mineralization has historically been spatially associated with the southern base of the greenstone belt and the Red Paint fault zone, which is where the majority of the mineral occurrences are located (*see* Figure 15.1B Mineral Deposit Inventory locations). Several base (Cu, Zn, Pb) and precious (Au, Ag) metal occurrences were sampled and documented during the bedrock mapping. Two general types of mineralization have been found in the belt: stratabound mineral occurrences and shear-hosted occurrences.

Mafic metavolcanic rocks in the Lumby South and locally within the Lumby North and Pinecone depositional sequences commonly contain centimetre- to decimetre-scale gossans within pillow selvages, which contain small amounts (trace to 2%) of pyrite ± pyrrhotite. These are interpreted to be the result of synvolcanic sulphide minerals deposited on the paleoseafloor. Lack of a trap, such as a tuffaceous layer, allowed for the dissipation and deposition of these sulphide minerals within pillowed sequences. Several stratabound lead-zinc-copper-silver occurrences are hosted by sheared felsic tuffs between Lumby and Spoon lakes. These mineral occurrences are always found within dextral sheared felsic tuffs that are sericite-chlorite-quartz altered. Mineralization commonly includes pyrite ± pyrrhotite ± sphalerite ± chalcopyrite ± galena ± native silver in stringers and massive disseminations. These occurrences are interpreted to be volcanogenic sulphide mineralization (R. Bernatchez, Consulting Geologist, personal communication, 2009) related to a volcanic epicentre located south of Lumby Lake, where the synvolcanic quartz-feldspar porphyry tonalite intrusion is located.

Other stratabound mineral occurrences are located west of Lumby Lake (UTM 620656E 5432779N, NAD83, Zone 15) and south of Core Lake (UTM 620469E 5435303N, NAD83, Zone 15). The occurrence west of Lumby Lake is within a rusty weathered felsic tuffaceous unit, traced along strike for 300 m with a width of at least 20 m. It is a highly altered and foliated quartz-phyric unit consisting of fine-grained sericite, plagioclase, chlorite and biotite, and medium-grained arsenopyrite and pyrite. The sulphide minerals occur in foliation-parallel stringer veinlets and comprise 10 to 20% of the rock unit. Jackson (1985a) reported values of 0.25% Zn, 0.06% Cu and trace lead and gold from a 9.6 m channel sample. The Core Lake occurrence is hosted by a rusty weathered felsic tuffaceous unit with 30 cm wide, fine-grained, quartz veins that are associated with fine-grained sericite, ankerite and possibly sphalerite along the margins. Later oblique veins are associated with medium-grained (0.5 to 1 mm) disseminated pyrite and chlorite.

The gold occurrences within the Lumby Lake greenstone belt are generally hosted by the reactivated east-trending and the northeast-trending D<sub>2</sub> shear zones, although the origin of the gold is not fully understood. The nearby Hammond Reef project of Brett Resources Ltd. is hosted in a northeast-trending structure, similar to the orientation of D<sub>2</sub> faults. Directly south of Two Bay Lake (UTM 619140E 5432292N, NAD83, Zone 15), trenched mafic metavolcanic rock is exposed near the southern tonalite contact. The host metavolcanic rock is highly altered and consists of plagioclase, chlorite, ankerite and sericite. Two to three generations of quartz veins cut the rock. The early veins are S<sub>1</sub>-parallel, cherty, crack-seal quartz veins that are up to 20 cm wide. They host ankerite, chlorite, sericite and pyrite and are associated with strong sericite, ankerite and pyrite alteration of the metavolcanic host rock. The later quartz veins are coarse grained, oblique to the early veins and are not associated with strong alteration. A second trenched outcrop located directly south of Bufo Lake (UTM 619609E 5432044N, NAD83, Zone 15) consists of a poorly exposed area with tonalite cut by a thin quartz vein. The quartz vein is 15 cm wide and includes chlorite and ankerite alteration. No sulphide mineralization or visible gold was identified at this location. Another occurrence is located to the east of Red Paint Lake (UTM 618467E 5434347N, NAD83, Zone 15) and is very similar to the Two Bay Lake south occurrence. It is hosted by altered and sheared mafic metavolcanic rocks that are rusty brown on weathered surfaces. The mineralogy includes chlorite, sericite, plagioclase, ankerite and quartz, with fine-grained pyrite forming the rusty weathering. Two generations of quartz veins cut the rock: the early cherty crack-seal veins are S<sub>1</sub> parallel and are associated with sericite and ankerite alteration, whereas the late coarse-grained quartz fractures are oblique to S<sub>1</sub> and are not associated with any alteration. Mineralization was not observed.

Ultramafic rocks within the greenstone belt have been previously underexplored for copper-nickel-platinum group element (PGE) potential, particularly the intrusive ultramafic rocks. Several ultramafic to mafic sills and stocks were mapped within the greenstone belt and sampled for copper-nickel-PGE mineralization. Magmatic sulphide mineralization was found locally in these intrusions as 2 to 3 mm blebby or disseminated pyrite ± pyrrhotite ± chalcopyrite ± pentlandite. They occurred as trace to 5%

mineralization within the mafic and ultramafic rocks. These intrusions may be viable exploration targets due to the proximity to iron formation and metasedimentary rocks in the Pinecone assemblage, from which they may have scavenged sulphur.

## INTERPRETATION

The 4 depositional sequences suggest a dynamic volcanic environment in the Lumby Lake greenstone belt. The oldest age within or adjacent to the greenstone belt is *circa* 3014 Ma for the felsic tuff from the Lumby North depositional sequence (Tomlinson et al. 2003). This age predates the oldest age from the Marmion batholith at *circa* 3001 Ma (Tomlinson et al. 2003), implying that the felsic tuff of the Lumby North depositional sequence is not related to the Marmion batholith, unlike the Lumby South depositional sequence which formed on top of it. The intrusive synvolcanic quartz-feldspar-porphyrific tonalite that directly overlies the Marmion batholith south of Lumby Lake is interpreted to be part of the volcanic edifice responsible for the deposition of the southern felsic tuffs. These felsic tuffs are of very similar age to the Marmion batholith (*circa* 3000 Ma to 2998 Ma; Tomlinson et al. 2003), indicating a small span of time of formation for the volcanic edifice and deposition of the tuffs. The differing age range and morphology of the tuffs in the north and the south suggest that the tuffs in the North Lumby depositional sequence were deposited from a separate volcano that is not preserved, perhaps due to the intrusion of Neoproterozoic granitoid rocks.

Following the deposition of the felsic tuffs in the Lumby South and Bar Lake depositional sequences, mafic volcanism dominated until the deposition of the quartz arenite. This event likely represents a shallowing marine environment where the quartz-rich sediments, possibly sourced from the Marmion batholith, were shed into the ocean. Subsequent to sedimentation, the Bar Lake tuff was deposited *circa* 2898 Ma (Tomlinson et al. 2003). This is a unique age of felsic tuff deposition within the Lumby Lake greenstone belt and was likely triggered by a renewed or separate thermal event. After the Bar Lake tuff deposition, mafic volcanism dominated again in a shallowing depositional environment documented by the presence of vesicles in the upper portions of the flow. Tuff deposition in the Lumby North depositional sequence ranges from *circa* 3014 Ma to 2963 Ma, representing a smaller span of felsic volcanism than in the south. The youngest recorded age in the Pinecone depositional sequence is *circa* 2830 Ma from the tuff interbedded with komatiitic flows. Thus, rocks of the Lumby North and Pinecone depositional sequences span more than 180 Ma, a more prolonged event than in the south. This implies that the northern assemblage continued to evolve for a longer time period while volcanism ceased earlier in the southern part of the belt. The Pinecone depositional sequence contains abundant iron formation, interbedded clastic and carbonate metasedimentary rocks and vesicles in the upper mafic volcanic units, further indicating a shallowing depositional environment toward the top of stratigraphy. Fralick, Hollings and King (2008) suggest that the Pinecone sedimentary sequence was sourced from upraised volcanic rocks and, due to the thinning of the sedimentary sequence to the east, only a limited sedimentary source area was available. The marbles within the sequence formed in shallower areas of the basin, whereas the iron formation would have formed in the deeper areas of the basin.

Previous work has attributed the reversal of facing indicators to a subhorizontal syncline with an east-trending axial trace in the centre of the belt (Woolverton 1960; Jackson 1985a, 1985b). The results of this study do not confirm this model since neither parasitic folds nor duplicate stratigraphy on either side of the fold axis were observed. Instead, the wide shear zone observed where the synclinal fold axis was proposed is interpreted to be a major structural break separating the northern and southern tectonostratigraphic assemblages. This D<sub>1</sub> fault is interpreted to have been initially a greenstone belt-wide thrust fault with later dextral shear reactivation. Subsequent D<sub>2</sub> deformation, which produced the sinistral Red Paint fault zone and associated faults, is interpreted to have caused the conjugate, dextral, transcurrent reactivation along D<sub>1</sub> faults of unknown (but assumed to be minor) offset. The differing

stratigraphy of the northern and southern tectonostratigraphic assemblages in the greenstone belt and the large D<sub>1</sub> thrust fault separating them suggests that the Lumby Lake greenstone belt formed roughly coevally as 2 separate Mesoarchean terranes later joined by a convergent boundary of unknown age. The direction of convergence is unknown, but a study of the detrital zircon grains within the Pinecone sedimentary sequence may provide insight into this problem.

Neoproterozoic geologic events within the Lumby Lake greenstone belt include the intrusion of the Norway pluton and Van Nostrand stock, dextral shearing along the margins of the greenstone belt, and the sinistral faulting along the Red Paint fault zone. These Neoproterozoic structural events overprint all Mesoarchean structures.

## FUTURE RESEARCH

Mapping during the 2009 field season has addressed some of the outstanding geoscience questions regarding the Lumby Lake greenstone belt, but more remain to be addressed. The age and geochemical affinity of the mafic and ultramafic intrusions within the greenstone belt is untested, but samples for geochemistry and geochronology are being analyzed in order to establish their age. The gabbroic rocks are interpreted to be synvolcanic, but the relationship between the ultramafic plutonic rocks and the komatiite flows is unknown. Furthermore, the economic potential of these ultramafic intrusions is underexplored. Another geologic problem is the relationship between the tonalite overlying the Marmion batholith and the felsic tuffs higher in the stratigraphy. Dextral shearing along the base of the greenstone belt would have offset the location of the volcanic edifice relative to the tuffs making it difficult to locate which tuffs were deposited directly over the edifice. This has a potential impact on volcanogenic massive sulphide exploration. The geochemistry of the tonalite and the felsic tuffs needs to be compared in order to establish a correlation.

Lastly, the tectonic history of the belt remains unresolved. The new hypothesis presented here requires new U/Pb geochronology and detailed geochemistry focussed on the nature of the volcanic assemblages looking for progressions or breaks that could represent tectonostratigraphic boundaries. To examine this, geochronology on the metasedimentary rocks within the Pinecone depositional sequence is essential to determine if the convergence is Mesoarchean or Neoproterozoic in age. A detrital zircon study of the sediments will also provide valuable insight into the nature of the sediments and perhaps the direction of subduction between the northern and southern tectonostratigraphic assemblages. It is hoped all of these will produce enough data to establish a hypothesis on the formation of the greenstone belt and whether there are 2 separate distinctive terranes that converged together in the Mesoarchean or Neoproterozoic. The relative timing of the deposition of stratigraphy, intrusion of plutonic and mafic to ultramafic rocks with the structural geology and mineralization is also unknown and will be analyzed as part of the study.

## ACKNOWLEDGMENTS

The authors would like to thank the Lumby Lake 2009 field crew: Colin Purdy, Alaina Hills, Alex Berger and Eric Rock for all of their hard work as field assistants. We would also like to thank Ray Bernatchez and Karl Bjorkman for discussion and the identification of key outcrops. Thanks to the support of the Atikokan Mineral Development Initiative and Garry Clark and also to the town of Atikokan for their hospitality and overall friendliness. Lastly, we would like to thank Greg Stott for extensive discussion during and after the field season.

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# 16. Summary of Geophysical Projects and Activities

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## SUPPORT FOR THE BEDROCK MAPPING PROGRAM

Geophysical support for the bedrock mapping program continued to be a priority in 2009. Publicly available geophysical data sets were used to create suites of georeferenced images of magnetic, electromagnetic, radiometric and gravity products for each of the mapping areas. Derivative images of the data sets were tailored according to the nature of the project and the characteristics of the data. Prior to the start of the Lumby Lake mapping, an interpretation workshop was held to integrate the newly released Lumby–Finlayson helicopter-borne electromagnetic (EM) and magnetic survey results with the existing geological information in order highlight areas where additional mapping is required.

Geophysical support was provided for the following projects:

- Lumby Lake
- Bending Lake
- Pecors–Whiskey Lake
- Wabigoon synthesis
- Miminiska–Fort Hope compilation

Geophysical support for the Wabigoon synthesis is part of a new multi-year regional study, combining compilation work with new geological mapping. The Miminiska–Fort Hope compilation was published in 2009 and was a multi-year project that incorporated sparse geological information with regional geophysics (Madon, McIlraith and Stott 2009).

## GEOPHYSICAL DATA SET RELEASES FOR 2009

The following 8 geophysical data sets (GDS) were released during 2009. Table 16.1 lists these geophysical data sets and Figure 16.1 shows the locations of the geophysical surveys.

The data sets comprise a total of 116 442 line-kilometres of airborne surveys. Of the 8 data sets, the Lumby–Finlayson lakes and Marmion Lake area surveys were flown as part of the Atikokan Mineral Development Initiative (AMDI). The Detour Lake, Burntbush Lake and Shining Tree area surveys were flown under the auspices of the Discover Abitibi Initiative (DAI). The Ontario Geological Survey was responsible for publishing these data sets, but the actual management of the survey work was conducted by AMDI and DAI, respectively. The Mine Centre, Chatham and Night Hawk Lake area surveys were acquired as part of the OGS core program. The Night Hawk Lake survey was a purchased proprietary data set, whereas all of other surveys were newly commissioned.

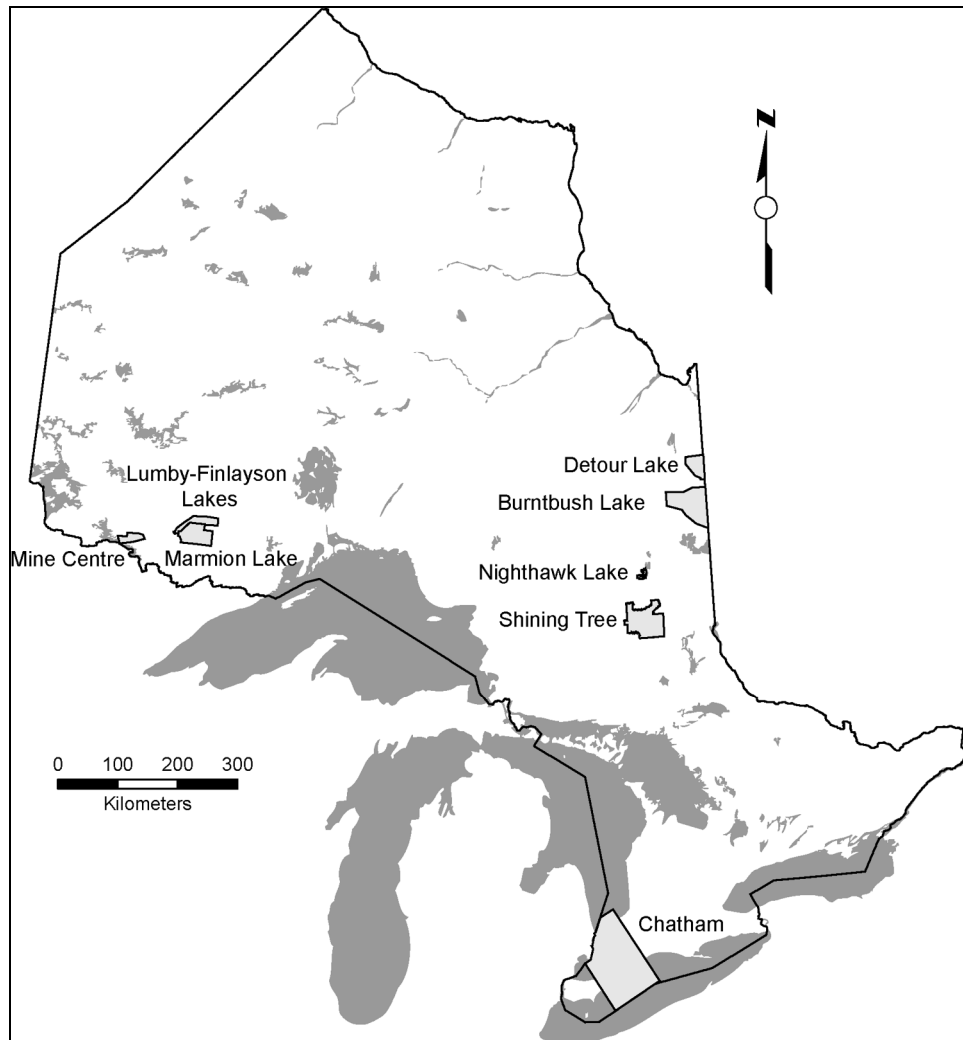
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*Summary of Field Work and Other Activities 2009,  
Ontario Geological Survey, Open File Report 6240, p.16-1 to 16-4.*

**Table 16.1.** Summary of geophysical data sets released by the Ontario Geological Survey in 2009.

GDS	Survey Name	Year of Survey	Survey Type	Line-km	Line Spacing
1060	Lumby–Finlayson lakes area	2009	Mag: total field EM: AeroTEM III (TD)	5294	200
1061	Mine Centre area	2009	Mag: total field EM: AeroTEM IV (TD)	3033	200
1062	Detour Lake area	2008	Mag: total field	10 791	100
1063	Burntbush Lake area	2008	Mag: total field	35 649	100
1064	Shining Tree area	2008	Mag: total field	23 662	150
1065	Chatham area	2009	Mag: horizontal gradiometer	24 604	50
1066	Marmion Lake area	2009	Mag: horizontal gradiometer	11 896	150
1231	Night Hawk Lake area	2007	Mag: total field EM: AeroTEM II (TD)	1513	100

Abbreviations: Line-km = line-kilometres; EM = electromagnetic; Mag = magnetic; TD = time domain

**Figure 16.1.** Location of geophysical surveys released as Geophysical Data Sets during 2009.

## REQUEST FOR DATA

From time to time, the OGS solicits companies for the purpose of purchasing digital airborne geophysical data. The process, known as a Request for Data (RFD), is intended to take advantage of the fact that many companies have airborne geophysical data from which they have already obtained full value and are prepared to have them released publicly. The benefits of purchasing the data are fourfold:

- low cost relative to acquiring new data
- data can be obtained about areas for which there is a lack of published surveys
- companies are able to invest the proceeds from the sale of data into further exploration work
- the reduced cost of acquisition frees funds for the OGS to fly surveys in other areas

Requests for Data are published on the MERX procurement Web site ([www.MERX.com](http://www.MERX.com)) and prospective vendors are required to download the document and complete the submissions forms appended to it. Submissions comprise single-page metadata sheets along with 2 other forms providing basic information about the vendor company; the digital data are not required at this stage. The information from the metadata sheets, which list such parameters as location, survey type, size and year the survey was flown are used to rank the surveys. Companies, whose surveys are considered to be of potential interest, are then contacted to provide a copy of the digital data so that they can be inspected for quality and completeness. Following the inspection of the data, and provided the data are considered to be up to industry standards, a discounted purchase value is calculated, based on survey type, age, quality, line spacing and whether they have already been submitted for assessment. An offer is then made to the vendor for the purchase of the data. Once acquired, the data are reprocessed, to conform to OGS standards, and released as hard-copy maps and in digital form.

Following a well-subscribed RFD, the OGS purchased 11 airborne surveys in March 2009 (Table 16.2). The surveys comprise 58 600 line-kilometres magnetic data mostly with electromagnetic data from 8 companies for a total cost of \$777 000. It is estimated that it would have cost the OGS \$3.8 million to fly these surveys. Three of these surveys are currently being reprocessed and will be released in early 2010. A previously purchased survey, Night Hawk Lake, was published in February 2009.

**Table 16.2.** Summary of airborne geophysical data sets purchased in March 2009.

Vendor Name	Survey Name	Survey Type
Canadian Arrow Mines Ltd.	Kenora Properties	Helicopter TDEM/magnetic
Chalice Diamond Corp.	Rennie Block	Helicopter TDEM/magnetic
Chalice Diamond Corp.	Chapleau Main block	Helicopter TDEM/magnetic
Chalice Diamond Corp.	Aguonie–Corbiere–Cowie–Esquega townships	Helicopter TDEM/magnetic
Golden Chalice Resources Inc.	Chapleau Project (Bird, Bader)	Helicopter TDEM/magnetic
First Canadian Uranium Inc.	Elliot Lake Area	Helicopter TDEM/magnetic
First Nickel Inc.	Raglan, Mayo, Carlow, Limerick, Wollaston Lake, Marmora & Belmont twps.	Helicopter TDEM/magnetic
International Montoro Resources Inc.	Serpent River	Helicopter TDEM/magnetic
Verbina Resources Inc.	Gaiashk Property	Helicopter TDEM/magnetic
Whestone Minerals Inc.	Pipestone Project	Total field magnetic
Whestone Minerals Inc.	Warclub Project	Total field magnetic

Another Request for Data was issued in June 2009 to acquire proprietary geophysical data in the Far North of Ontario and another Request for Data will be issued in the fall of 2009 to acquire data throughout all of Ontario.

## MAGNETIC SUSCEPTIBILITY COMPILATION

Field geologists in the Precambrian Geoscience Section continued to collect magnetic susceptibility measurements during the mapping programs, using Exploranium™ KT-9 Kappameter instruments. Compilation of data collected from the years 2001 to 2008 are being processed and will be released at the end of 2009 as a Miscellaneous Release—Data (MRD). The MRD will consist of a Microsoft® Excel® spreadsheet and an ESRI® ArcGIS® geodatabase, which will include data from 8 field seasons involving 26 projects, totalling approximately 16 350 stations with up to 10 readings per station.

## OTHER ACTIVITIES

The Web-based Geophysical Atlas ([www.mndm.gov.on.ca/mines/ogs/gpxatlas/default\\_e.asp](http://www.mndm.gov.on.ca/mines/ogs/gpxatlas/default_e.asp)), which facilitates the discovery of published geophysical data in Ontario, has been maintained and updated with newly released surveys.

The GeologyOntario Web portal ([www.mndm.gov.on.ca/mines/geologyontario/default\\_e.asp](http://www.mndm.gov.on.ca/mines/geologyontario/default_e.asp)) allows the free download of the OGS geophysical data sets, except for profile and halfwave EM data due to their file size.

Alternatively, hard-copy (paper) maps and physical media (CD or DVD) of digital data continue to be available for purchase through

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As part of the OGS service to clients, the following geophysical presentations were made during 2009:

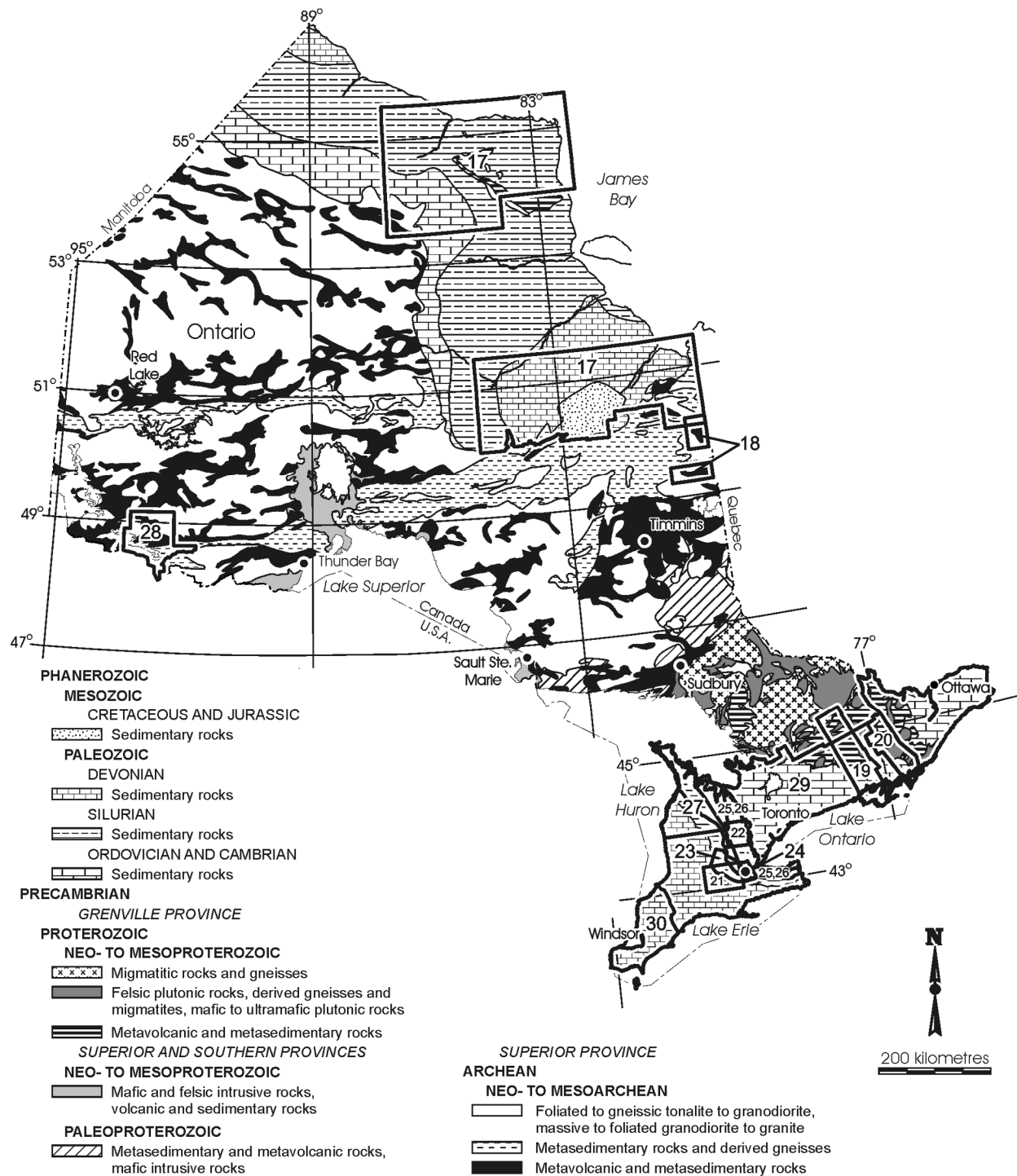
- a course for geologists and prospectors presented in conjunction with the Ontario Prospectors Association Northwestern Ontario Mines and Minerals Symposium in Thunder Bay;
- a component of a multi-day post-graduate-level course in geophysical exploration at Laurentian University in Sudbury

## REFERENCES

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# **Sedimentary Geoscience Section**

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Location of Sedimentary Geoscience Section projects for 2009–2010. Numbers correspond to article numbers.

# 17. Project Unit 08-008. Far North Terrain Mapping Project

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## INTRODUCTION

Field work for the Far North Information Knowledge Management (FNIKM) Plan Terrain Mapping project (Barnett et al. 2008) began during the summer of 2009, with field excursions taking place in the James Bay and Hudson Bay lowlands. Field work conducted over separate one- and two-week periods during July and August was helicopter supported. The writer was accompanied in the field by personnel from the FNIKM Land Cover (Adam Hogg and Paul Sampson) and Hydrology (Kent Todd) project teams. The joint approach of this field work, combining the expertise of land cover, hydrology and surficial geology interpretation, was very successful with each participant learning from the other. The co-ordinated approach for information collection and the understanding gained from this approach should bode well in the planning of future field work, the interpretation of remotely sensed imagery and in the creation of the final products of the 3 FNIKM projects involved.

A key component of the field work was making observations of landform–sediment relations combined with observations of the associated vegetation communities. The understanding of these associations is vital to the project’s goal of remotely predicting the distribution of surficial materials in the Far North of Ontario. Observations of sediment type were done primarily by hand auger, test pits and the observation of natural exposures along rivers, streams and the sea. Samples of selected sediments, primarily of till, were collected for the analysis of particle size, carbonate content and trace element geochemistry.

During field work, support was supplied to Ontario Geological Survey colleagues, John Ayer, Greg Stott and Sara Buse to collect rock samples for geochronology, paleomagnetic properties and samples for rock geochemistry. In addition, 2 cores were collected from peat bogs for the FNIKM Peatlands and Climate Change Research Project and logistical support was provided to members of the FNIKM Biodiversity and Caribou projects.

Remote prediction of the distribution of surficial materials continued through the summer using remotely sensed imagery including, Landsat ETM, Spot and a digital elevation model (SRTM). In this project, the object-based Definiens Developer 7™ software is the primary software being used for remote sensing, whereas ERSI® ArcMap™ and ArcPad™ are employed for desktop and mobile GIS applications. Results to date are promising and work will continue throughout the remainder of the year. Digitizing of the numerous shoreline features in the lowlands commenced this summer following the release of the flow indicator map for the Far North of Ontario (Barnett, Webb and Hill 2009) and will be used as a symbol layer on the surficial materials maps that will be produced during this project.

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*Summary of Field Work and Other Activities 2009,  
Ontario Geological Survey, Open File Report 6240, p.17-1 to 17-5.*

## FINDINGS

The details of the field observations made during the 2 field excursions are still being organized and interpreted. However, the terrain of the Moose River basin and the Hudson and James Bay lowlands is dominated by low-relief marine plains, which, in places, are deeply dissected by rivers and creeks exposing a wealth of information about glacial, nonglacial and preglacial time in this area (Skinner 1973). Local relief can exceed 90 m along the Sutton Ridges (Rabbit Ridge), which consists of rounded hills, buttes and mesas formed of diabase sills overlying layers of banded iron formation, chert clast breccias and conglomerates, and carbonate rocks, all of which are Precambrian in age (Sanford, Norris and Bostock 1968; Bostock 1971). Large parts of the ridges are rounded and shaped by glaciation. Photo 17.1 displays an example of 2 large *roches moutonnées* that make up part of the Sutton Ridges. Elsewhere, Paleozoic, Mesozoic and Tertiary rocks underlie the lowlands and outcrops of these rocks occur along the coasts of Hudson Bay and James Bay and along many of the rivers that dissect the lowlands (Sanford, Norris and Bostock 1968; Photo 17.2).

The Quaternary succession is usually thick and consists of several glacial and nonglacial sediment sequences, the details of which are also exposed primarily along the rivers and creeks of the lowlands (Skinner 1973; Thorleifson, Wyatt and Warman 1993). A few river and sea exposures were visited during field work: some to become familiar with the stratigraphy as it is known and other exposures to collect new information (Photo 17.3). Field stops to investigate the geological material and vegetation cover associated with various landforms throughout the lowlands were also made. The distribution of field sites visited is depicted in Figure 17.1. In addition to stops at various types of wetlands and the extensive marine plains, marine shorelines (Photo 17.4), drumlins and ice margin depositional features were also investigated.



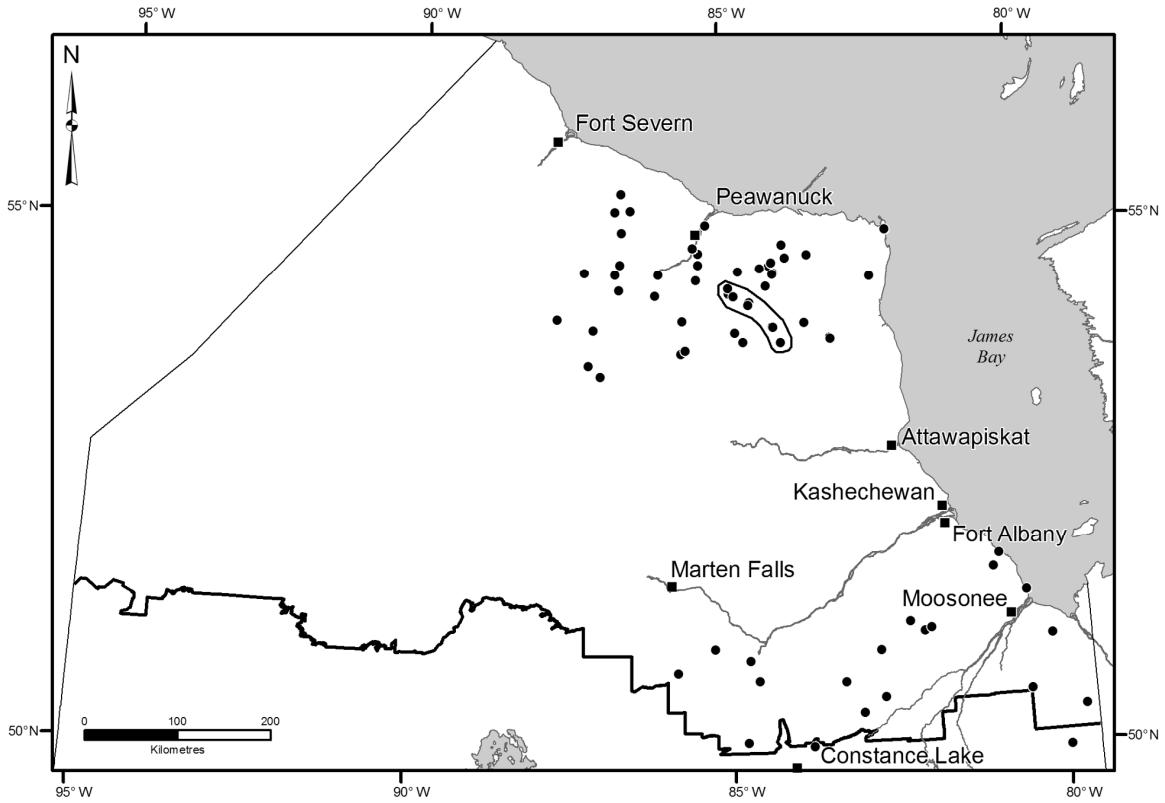
**Photo 17.1.** Extensive area of outcrop associated with the rounded back of a diabase sill of the Sutton Ridges. Local relief exceeds 90 m on the southern flank of the sill-controlled bedrock ridge. Typical lowland topography occurs in the distance below the horizon. The part of the Sutton Ridges pictured here is composed of 2 large *roches moutonnées*.



**Photo 17.2.** Exposure of the Silurian, Severn River Formation along the Shamattawa River, near Peawanuck, Ontario. Note the stratigraphic control of the discharge of groundwater along this stretch of river.



**Photo 17.3.** A multiple till exposure located along the Winisk River about 180 km south-southwest of Peawanuck, Ontario.



**Figure 17.1.** Location of sites visited during the summer of 2009 and the location of the Sutton Ridges (oval).



**Photo 17.4.** A series of recurved spits formed in the Tyrell Sea, about 150 km west-southwest of Moosonee, Ontario. The area has experienced a forest fire. The forest cover associated with the dryer sand and gravel deposits of the spits has burned preferentially to the surrounding forested wetlands.

Four sets of streamlined glacial landforms were observed in the southern part of the Hudson Bay Lowland that was investigated. The landforms indicate glacial flow to the west-northwest, west-southwest, south-southwest and south to south-southeast (oldest to youngest?). Samples were collected from all of these sets and are currently being analyzed.

## CONCLUSIONS

The joint approach of this project in bringing scientists of differing backgrounds together proved to be a very rewarding experience and should bode well in the future production of surficial material maps using remotely sensed data for the Far North of Ontario.

## ACKNOWLEDGMENTS

The authors gratefully acknowledge the funding for this project by the Ministry of Natural Resources and the Ministry of Northern Development, Mines and Forestry. The writer would like to thank Adam Hogg, Paul Sampson and Kent Todd (MNR) and Danielle Partington (MNDMF) for the assistance they provided during field work for this project and Kei Yeung for his help during field work preparation. Danielle began the large task of digitizing shoreline features and Kei continued the effort in remote prediction of surficial sediments in the office. In addition, the overall support of this project from the Constance Lake, Moose Cree and Weenusk First Nations is gratefully appreciated.

The Ministry of Natural Resources provided transport to and from the field and helicopter support; the work of all the MNR pilots was appreciated. Flight watch in Peawanuck was provided by Mike Hunter who also shared with us his wealth of knowledge of the land. Rod Brook (MNR) provided logistical advice.

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# 18. Project Unit 08-005. Update on Surficial Mapping and Till Sampling in the Detour Lake and Burntbush Areas, Northeastern Ontario

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## INTRODUCTION

Field investigations for a surficial mapping and till sampling project in the Detour Lake and Burntbush areas, northeastern Ontario, continued in 2009. In 2008, field work was conducted in the Burntbush area, north of Lake Abitibi (Gao and Day 2008), whereas this year, work was focussed in the Detour Lake area to the north (Figure 18.1). The project is designed to assist mineral exploration efforts as the thick and extensive surficial deposits covering bedrock have hampered mineral exploration in parts of the Abitibi greenstone belt located in northeastern Ontario (Figure 18.2). Surficial mapping was undertaken to document the distribution and character of the various Quaternary deposits in the region and to reconstruct the ice-flow and glacial history. Till sampling was conducted to help assess the regional mineral potential of the area for kimberlite (diamond), gold and base metals.

The map area is delineated on ten, 1:50 000 NTS map sheets in a north to south strip along the provincial border (*see* Figure 18.1). To assist mapping and sampling efforts in the field, a helicopter was used to access areas of poor accessibility, including the northern part of the Burntbush area. In the Detour Lake area, few roads exist; major roads are the Highway 652 (Detour Highway) and Translimit Road, both start at Cochrane. The former ends at the Detour Mine to the northeast, whereas the latter, a gravel road, extends eastward into Quebec.

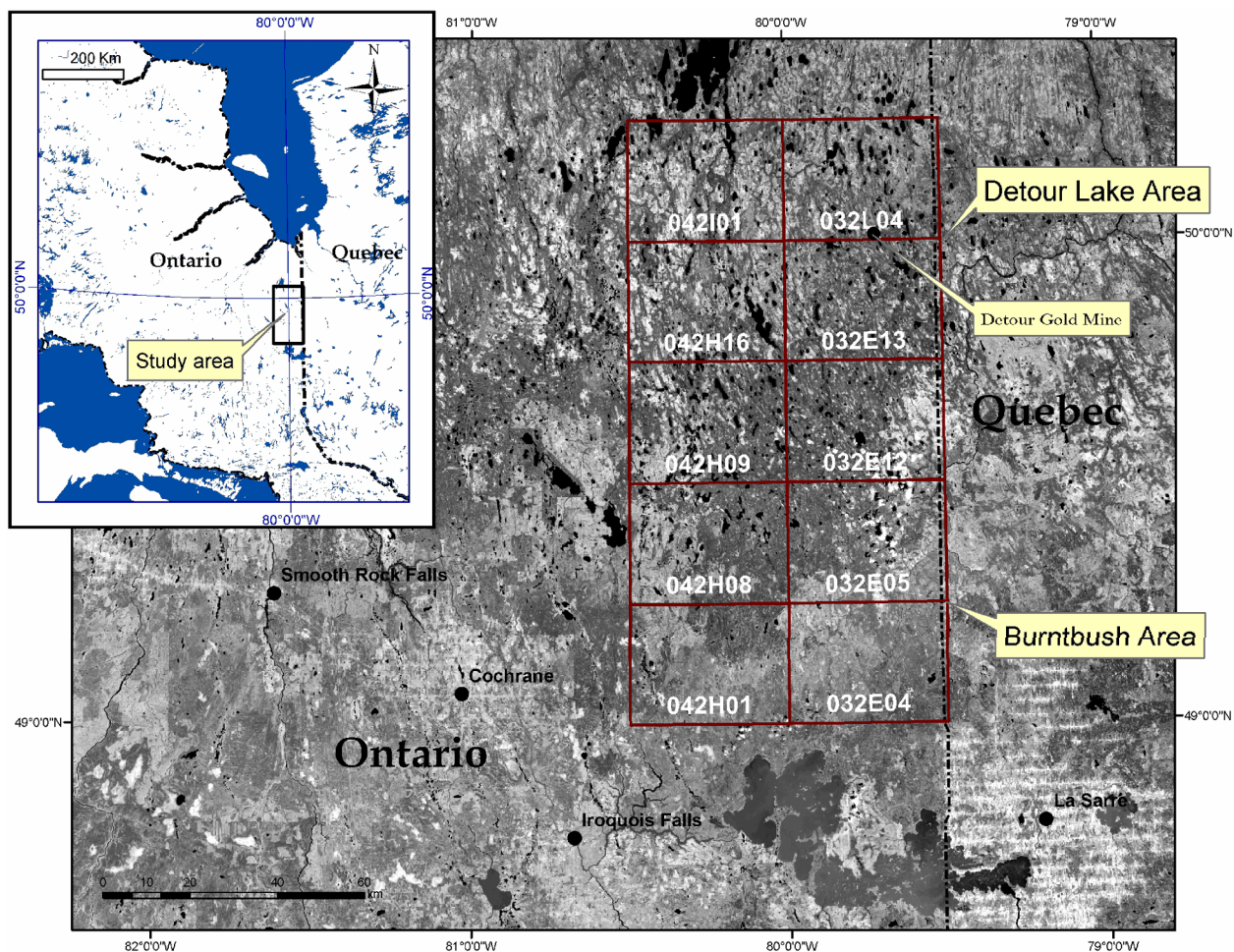
Bedrock in the map area consists of Archean supracrustal rocks of the northern Abitibi greenstone belt and Archean metasedimentary and batholithic granitic rocks (*see* Figure 18.2). The greenstone belt in the Detour Lake and Burntbush areas, which extends for over 400 km to the east into Quebec, contains mafic to felsic metavolcanic rocks with some metasedimentary and felsic to mafic intrusive rocks. After its closure in late 1990s, the Detour gold mine is currently undergoing a feasibility study for open-pit mining by Detour Gold Corp.

The report area, which was overridden by glacial ice during the Late Wisconsin Cochrane ice advance (Hughes 1960, 1961, 1965; Boissonneau 1965, 1966), is a flat to gently undulating clayey to silty till plain covered by peat and bog deposits of varying thickness, interrupted by occasional knobs or low hills of bedrock, in particular, in the southern part of the Burntbush area. The area is drained by 2 major rivers, the Burntbush and Detour rivers, which flow eastward to Quebec to join the River Harricana flowing to the north across the James Bay Lowland.

## FIELD WORK

Field work was conducted along highways, logging roads and trails. In areas where no roads exist, a helicopter was used for checking specific locations and for sampling, as well as for flyovers to verify large bedrock exposures interpreted from aerial photographs. Apart from roadcut sections, geological observations were also made through test pitting and by the use of a hand auger. Natural deep sections as exposed in streams and gullies are rare due largely to the flatness of the topography and lack of stream incision. Two global positioning system units, a GPSmap 60Cx and a GPSmap 60CSx, were used for navigation and location data in the field.

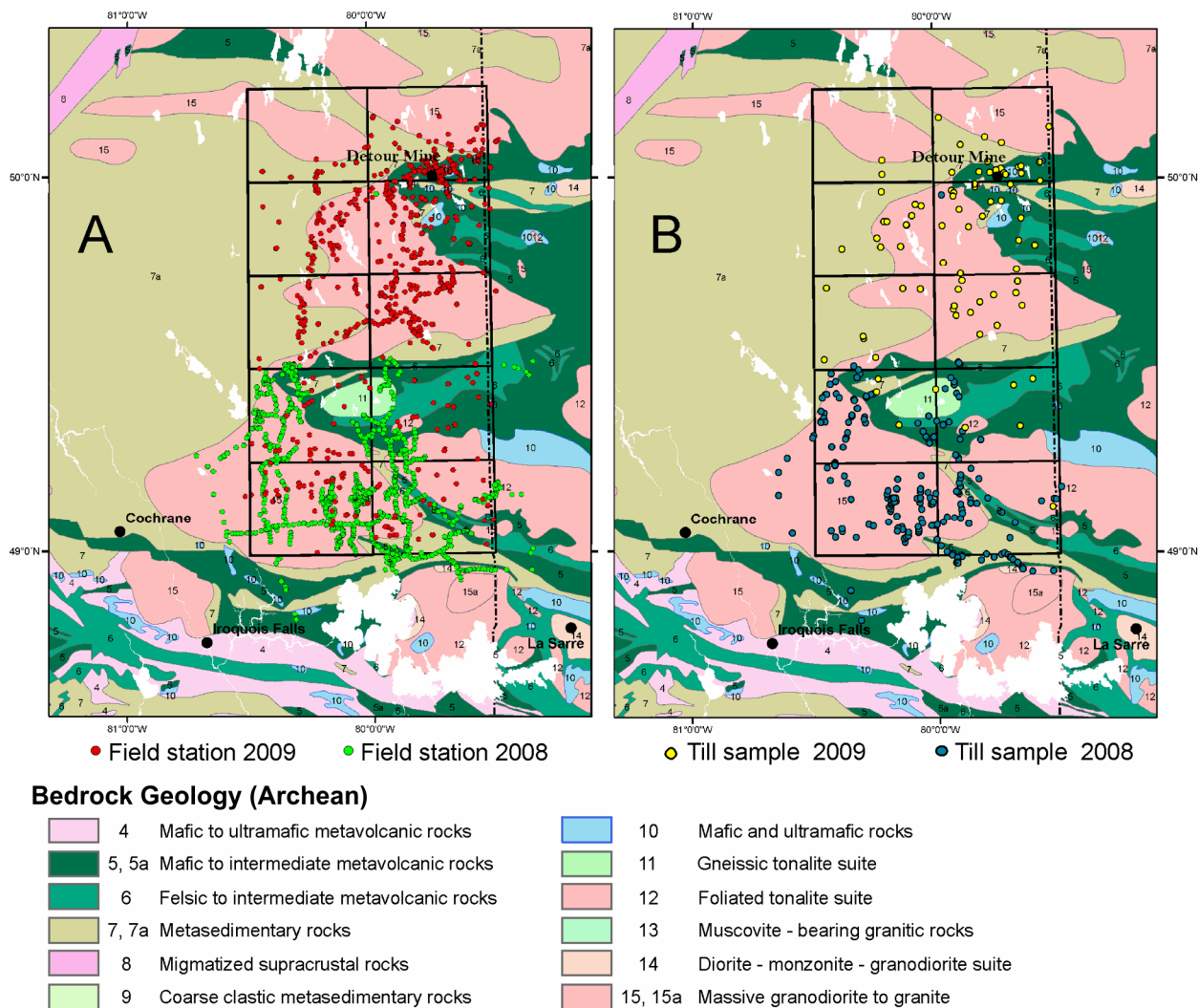
The major Quaternary deposits in the report area consist of till, glaciofluvial, glaciolacustrine, recent alluvium and bog deposits. Two regionally mappable Late Wisconsin till units exist: a sandy till and a silty till, both of which can easily be recognized in the field by their texture and pebble lithology. The former diamicton has a sand-rich matrix and often contains abundant cobbles and boulders, but with a low content of limestone clasts. The matrix, which shows various degrees of compactness and fissility, often consists of light-coloured fine-textured sand. In well-exposed pit sections, the lower part of the sandy till is compact and is “stone rich” with a strong fissility, whereas, its upper part is sometimes “stone poor” with reduced compactness and fissility. As opposed to the sandy till, the silty till has a silt and clay-rich



**Figure 18.1.** Location map of the study area, with the 1:50 000 scale NTS map areas labels superimposed. Inset shows the location of the study area.

matrix and is stone poor, but has a relatively high content of limestone clasts. This till has a brownish colour, and usually reacts with 10% HCl. Large boulders may occur at the base of the till. Both tills in dry conditions are easily broken up into small, thin slabs along horizontal and vertical joints that are abundant in the deposits.

The sandy till occurs mainly in the area covered by the 2 southernmost map sheets (NTS 42 H/1 and 32 E/4) in the Burntbrush area. To the north, the sandy till is observed only occasionally below the silty till in roadside ditches and sand pits. In the northeastern part of map area NTS 42 H/8, this till occurs as ridges and low hills above the surrounding lowland. The sandy till can probably be correlated to the Matheson Till mapped in the Matheson area (Hughes 1965). The silty till occurs extensively in the study area, covering glaciolacustrine and glaciofluvial deposits, and can probably be correlated to the Cochrane Till (Hughes 1965). The silty till is sometimes overlain by a thin layer of lacustrine silt and clay, which contains small clasts, frequently limestone, probably of ice-rafted origin. Unless adequately large exposures are present where laminations are visible, which is rarely the case in the field, this deposit is difficult to separate from the silty till and, as a result, is not mapped separately.



**Figure 18.2.** Bedrock geology (Ontario Geological Survey 1991) overlain with A) field stations where geologic observations and/or sampling were made; and B) sites where till samples were collected in 2008 and 2009.

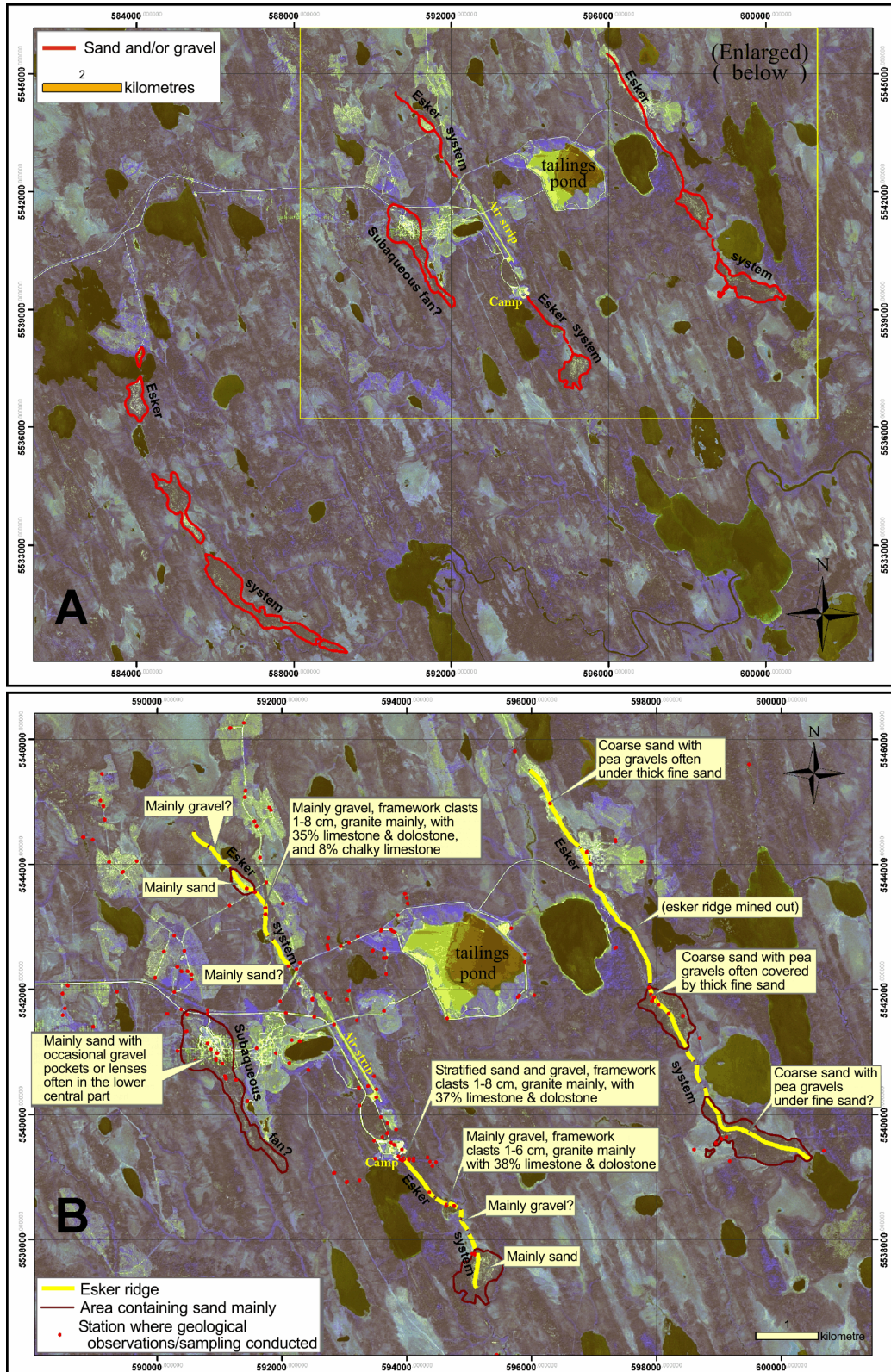
Borehole records indicate that both tills can reach a thickness of over 20 m; direct contact between the 2 tills was observed in a large sand pit in the central western part of map area NTS 32 E/5 where more than 4 m of light-coloured bouldery to sandy till is overlain by 1 to 3 m of brownish silty till (Gao and Day 2008). The borehole records also show the presence of a lower till below the sandy till. However, its relationship to the sandy till remains undetermined. Future detailed study and drilling in the area may provide insight into the occurrence and stratigraphic status of the lower till. Laminated to massive silt and clay of glacial lake Barlow–Ojibway occurs mainly in the southernmost part of the report area. In the north, fine- to very fine-textured sand of glaciolacustrine origin often occurs below the silty till. Postglacial peaty mud and peat, ranging from 1 to over 4 m in thickness, covers much of the swampy lowland area.

The northern part of the study area exhibits a fluted terrain that probably developed during the Cochrane ice advance. Flutes are commonly aligned in a south-southeast direction. Although the silty till frequent occurs in these features, the sandy till is also found in sharply fluted narrow ridges. These linear features sometimes show a crag-and-tail structure with a stoss bedrock head to the north.

It has long been suggested that the eskers, as well as the flutes were related to the Matheson ice advance, and that the subsequent Cochrane ice advance, which followed the flow direction of the previous ice sheet, only formed a capping till, without significantly scouring these features (Hughes 1965; Boissonneau 1966). Eskers checked in the field normally contain fine-textured gravels and coarse sand with rare boulders. These deposits are rich in limestone clasts, which comprise as high as 40% of the framework clastic material. The lithologies of the clastic material in the eskers appear to match the rock fragments of the silty till or Cochrane Till, suggesting that these eskers were emplaced during the Cochrane ice advance. This is further evidenced by the presence of rolled silty till clasts ranging from pebble to boulder size in the upper part of the eskers. This suggests that the silt till must be no younger than the emplacement of the eskers, and more likely was deposited contemporaneously or penecontemporaneously with the eskers (Photo 18.1). As such, active glaciofluvial and glaciolacustrine processes did occur during the Cochrane ice advance and retreat, forming mappable deposits such as eskers, flutes, as well as near-shore to deep basin deposits in proglacial lakes.



**Photo 18.1.** Rolled silty till clast in glaciofluvial sand in an esker complex. Coin is 2.1 cm diameter.



**Figure 18.3.** Eskers and other glaciofluvial deposits where gravelly material likely exists around the Detour gold mine. Note that the boxed area in A is enlarged and shown in B where details are added.

## PROJECT STATUS

More than 1200 data points were collected during examination of the material in the report area over the summer of 2009 (*see* Figure 18.2). This information, together with the data collected in 2008, will be used to generate surficial (Quaternary) geology maps for the report area. About 90 till samples were obtained in 2009, which are being processed for indicator minerals for kimberlite, gold, silver and base metals (*see* Figure 18.2). One of the preliminary results of this project is the identification of aggregate resources (eskers) near the Detour gold mine (Figure 18.3). The delineation of these resources will allow for the cost effective development of infrastructure in the area and promote economic growth.

## ACKNOWLEDGMENTS

Dan Belanger and Brian Packer provided valuable field assistance. The Detour Gold Corp. is thanked for providing accommodations, meals and gasoline, as well as for allowing access to its geotechnical drill core samples. The Ministry of Natural Resources (MNR) aviation section provided the helicopter support; Gord Bain, Rod Mitchell and Kevin Mulcair, the pilots, are thanked for their hard work and co-operation. The detailed review of this article by Cam Baker and Ross Kelly is greatly appreciated by the authors.

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# 19. Project Unit 09-022. Aggregate Resources Inventory of Hastings County, Southern Ontario

D.J. Rowell<sup>1</sup>

<sup>1</sup>Sedimentary Geoscience Section, Ontario Geological Survey

## INTRODUCTION

During the summer of 2009, an aggregate resources assessment of Hastings County was undertaken by the Sedimentary Geoscience Section of the Ontario Geological Survey. Hastings County is located north of the Bay of Quinte in southeastern Ontario and occupies 597 764 ha. It is bounded to the east by Lennox and Addington County; to the northeast and north by Renfrew County and the District of Nipissing; to the west by Haliburton, Peterborough and Northumberland counties; and to the south by Prince Edward County (Figure 19.1). The study area is covered by all or parts of the Belleville (31 C/3), Trenton (31 C/4), Campbellford (31 C/5), Tweed (31 C/6), Kaladar (31 C/11), Bannockburn (31 C/12), Coe Hill (31 C/14), Wilberforce (31 E/1), Whitney (31 E/8), Bancroft (31 F/4) and Barry's Bay (31 F/5) 1:50 000 scale map sheets of the National Topographic System (NTS).

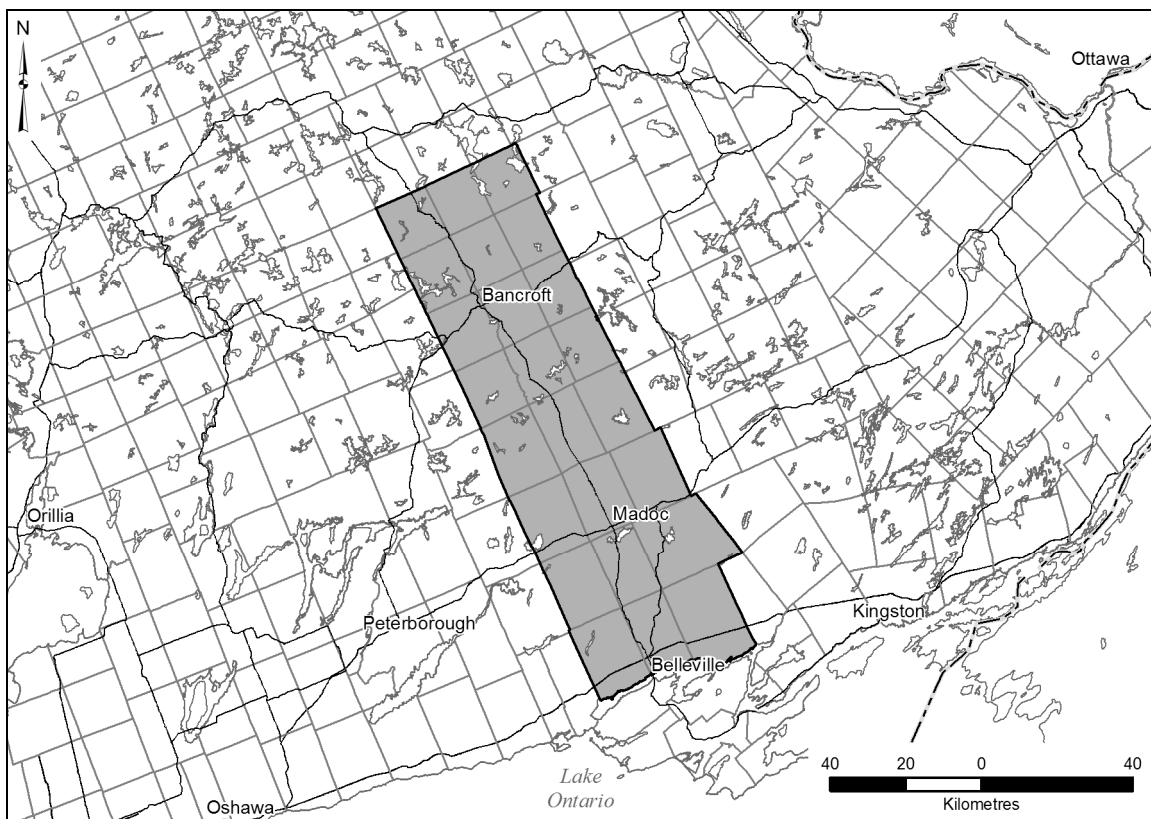


Figure 19.1. Location of Hastings County.

*Summary of Field Work and Other Activities 2009,  
Ontario Geological Survey, Open File Report 6240, p.19-1 to 19-8.*

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The purpose of the investigation was to delineate the aggregate deposits within the study area and to assess the quality and quantity of sand and gravel, and bedrock-derived aggregate resources. This information is required for infrastructure development and renewal, general construction applications and land use planning purposes.

## **SURFICIAL GEOLOGY AND PHYSIOGRAPHY**

The physiography and distribution of surficial material in Hastings County, including the sand and gravel deposits, are primarily the result of glacial activity that took place in the Late Wisconsinan (Barnett 1992). This period, which lasted from approximately 23 000 to 10 000 years before present, was marked by the repeated advance and retreat of the Laurentide Ice Sheet (Barnett 1992). The direction of ice movement in the study area is recorded by the orientation of striations, drumlins, crag and tail features, chattermarks and grooves. Ice flow in the northern part of Hastings County has been recorded in a generally north-south direction of 195° (Barnett 1983). Minor variations in ice flow direction do occur due to bedrock topography, but these variations tend to be minor and localized.

As the ice advanced, debris from the underlying soil and bedrock accumulated within and beneath the ice. The debris, a mixture of stones, sand, silt and clay was deposited over large areas of the county as till plains, drumlins and moraines. In the northern part of Hastings County, the hard, erosion-resistant Precambrian rocks provided little soil and weathered bedrock to the glacier. As a result, the northern part of the county belongs to the physiographic region known as the Algonquin Highlands, which is described by Chapman and Putnam (1984) as rugged and characterized by thinly till-covered rock knobs and ridges. Outcrops of bare rock are common and relief in the area is generally controlled by the Precambrian bedrock.

Drainage in this area is controlled by bedrock structures and type. Barnett (1983) noted that the Mississippi and York rivers flowed in river valleys that overlay less erosion-resistant Precambrian bedrock. For example, the York River seems to run almost exactly along strike of the crystalline limestone rocks with many of the abrupt turns apparently conforming to the contortions and twists of the strata. Many of these river valleys have subsequently been flooded with outwash sand and gravel (Chapman and Putnam 1984; Barnett 1983).

Located south of the Algonquin Highlands physiographic region, and crossing the entire county in a southeasterly direction, is the Napanee Plain. It is a flat to undulating plain of limestone from which the glacier stripped most of the overburden (Chapman and Putnam 1984). The plain is named for the community of Napanee, which is located east of the study area and is roughly the centre point of the plain (Chapman and Putnam 1984). Whereas the overburden is generally thin over much of the region, some areas of thick glacial till occur in stream valleys and toward the north near the Dummer moraine. There are also a few scattered drumlins that tend to be long, thin and shallow. The Salmon and Napanee river valleys provide relief of 15 to 30 m within the Napanee Plain physiographic region.

In southern Hastings County, the till cover begins to thicken and has been drumlinized. The texture of the till in this portion of Hastings County ranges from a gritty, silty sand to a sandy silt, moderately stony and compact (Leyland and Mihychuk 1983, 1984a, 1984b). Along the southwestern boundary of Hastings County and south of the Dummer Moraine physiographic region is the Peterborough drumlin field. The drumlin field extends from Hastings County in the east to as far as Simcoe County in the west (Chapman and Putnam 1984). The drumlins within the Peterborough drumlin field are generally oriented in a northeast-southwest direction, roughly from 200 to 220°. Drumlins just north of Belleville have a more westerly orientation of about 240 to 280° (Mirynech 1962). The till that comprises these more westerly oriented drumlins and the till plain has a higher percentage of Precambrian clasts than elsewhere

in the Peterborough drumlin field. As a result, Miryneck (1962) has suggested that the Peterborough drumlin field be split into the Peterborough and Quinte fields based on the orientation and physical characteristics of the drumlins. Miryneck (1962) also points out that the drumlins in the Quinte field are distinctly lower, narrower and more ridge like. The density of the drumlins is also lower, rarely exceeding 3 or 4 per km<sup>2</sup>.

During deglaciation, the Laurentide Ice Sheet split into glacial lobes that behaved semi-independently. The study area was affected by 2 ice lobes: one from the northeast (the northern lobe) and one from the southeast (Lake Ontario lobe). The contact between these 2 lobes is marked by the Oak Ridges moraine located to the west of the study area in Northumberland County. Deglaciation in the area was characterized by a general melting back of the ice mass. As the ice melted, meltwater streams within or beneath the melting glacial ice, filled with glaciofluvial sediments forming eskers such as those at Marbank, Tweed, east of Stirling, Limerick Lake, McArthurs Mills, Rutledge Lake and Little Papineau Lake. In general, these esker ridges all have a meandering southwest orientation with paleocurrent flow directions to the southwest. Esker length varies from about 3 to 80 km (Miryneck 1962). They represent a well-integrated glacial drainage system, one that is similar to and nearly coincident with the modern drainage system as well as the older bedrock valley system (Miryneck 1962).

As the ice margin continued to retreat and melt northeastward (northern lobe) and eastward (Lake Ontario lobe), the Dummer moraine was formed. Located to the south of the Algonquin Highlands, this physiographic region trends roughly parallel to the Paleozoic–Precambrian contact across Hastings County. Its northern boundary often coincides with this contact, but, occasionally, the moraine extends a short distance north of the contact. The Dummer moraine is characterized by a rough, hummocky, stony-bouldery landscape. Till comprising the Dummer moraine is composed of angular boulders and pebbles in a coarse sand matrix. Paleozoic clasts are predominant with Precambrian clast content as low as 2% (Finamore 1982; Leyland and Mihychuk 1983, 1984a, 1984b). The origin of the Dummer moraine is not well understood. Gravenor (1957) and Miryneck (1962) believe that the Dummer moraine represents a recessional moraine formed during the latter stages of deglaciation in the study area and this is why this physiographic region is described here in the glacial sequence (during the retreat and melting stage). These authors believe that the northern lobe had a slight readvance that carried local material a very short distance. Shulmeister (1989) and Brennand and Shaw (1994) offer alternate theories on the age and formation of the Dummer moraine, which puts its formation earlier in the glacial history of Hastings County.

As melting continued, large volumes of meltwater flowed into the Lake Ontario basin forming glacial Lake Iroquois. About 12 300 years ago, glacial Lake Iroquois occupied the western end of the Lake Ontario drainage basin (Barnett 1992). The glacial lake drained through an outlet at Rome, New York. In the study area, glacial Lake Iroquois expanded northeastward and flooded an area that is referred to as the Trent Embayment. In this embayment were a number of wave-washed islands. While Lake Iroquois occupied this area, fine-grained silt and clay were deposited in plains near Stirling and coarser grained sand was deposited in other parts of the study area. The area that was occupied by glacial Lake Iroquois and the Trent Embayment formed the physiographic region known as the Lake Iroquois Plain (Chapman and Putnam 1984). The Iroquois Plain extends to the western end of Lake Ontario where it is often better defined and delineated because of the presence of large beach ridges and terraces. Deposits of glaciofluvial origin are often capped by beach material, such as Pancake Hill in Centre Hastings and Sullivan's Hill in Quinte West. In southern Hastings County, observed elevations in numerous small ancient beach ridges record at least 6 glacial lake events (Miryneck 1962). The 6 lake levels include glacial lakes Iroquois, Frontenac, Sydney, Belleville, Trenton and Admiralty (Miryneck 1962).

## SAND AND GRAVEL RESOURCES

In the northern part of Hastings County, large outwash deposits provide readily available and accessible sources of sand and gravel. These glaciofluvial outwash deposits have been deposited by glacial meltwater in rivers and streams flowing beyond the glacier's margin. Well-developed deposits are uniform in grain size over a considerable area and gradually become finer textured further away from the glacier. This uniformity makes this type of deposit a good source of aggregate material.

In highland areas, the outwash deposits are not as well developed. In general, meltwater channels were narrow and bedrock controlled. As a result, irregularities in the bedrock surface and trapped blocks of abandoned glacier ice disrupted the flow of meltwater within these narrow valleys resulting in the lack of uniformity of these outwash deposit sediments.

In the southern part of Hastings County, the main source of good quality sand and gravel are the long sinuous esker ridges and some of the larger, well-developed beach deposits. The glaciolacustrine sand deposits located in the southern part of Hastings County are generally too fine grained to be used in aggregate production, although the material from these deposits can be used for fill. A number of sand and gravel samples were collected over the course of this study and have been submitted to the Ontario Ministry of Transportation for standard aggregate testing.

## BEDROCK GEOLOGY

The northern portion of Hastings County is underlain by metamorphic and igneous Precambrian rocks of the Grenville Province, whereas the southern part of the county is underlain by a succession of relatively flat-lying sandstones, limestones, dolostones and shales of Paleozoic age. Paleozoic rocks also occur as outliers within areas dominated by Precambrian rock.

The Precambrian rocks include metamorphosed volcanic rocks, clastic and chemical sediments and plutonic rocks of Mesoproterozoic (0.9 to 1.6 Ga), and Neo- to Mesoproterozoic age (0.57 to 1.6 Ga) (Easton 1992). The rocks belong to the Central Gneiss Belt, generally in the north, and the Central Metasedimentary Belt in the central part of the county (Easton 1992). Thivierge (1983) reports the metamorphic grade is high in this part of Hastings County, from upper amphibolite facies to minor occurrences of hypersthene granulite facies. Detailed mapping and discussion of the Precambrian rocks is provided in the following references: Breaks and Thivierge (2001), Di Prisco, Hammar and Easton (2001a, 2001b), Easton (1992, 2001a, 2001b, 2001c, 2008a, 2008b), Easton and Ford (1994a, 1994b) and Lumbers and Vertolli (1998, 2000a, 2000b, 2000c).

The Precambrian basement is unconformably overlain by the Shadow Lake Formation. This unit is the oldest Ordovician formation in central and southwestern Ontario (Johnson et al. 1992). It is also the basal unit of the Black River Group (Armstrong and Carter 2006). The Shadow Lake Formation consists of poorly sorted, red and green sandy shales; argillaceous and arkosic sandstones; minor sandy argillaceous dolostones; and rare basal arkosic conglomerate (Armstrong and Carter 2006). Two members have been identified by Carson (1980a, 1980b, 1981a, 1981b): a lower sandy member and an upper dolomitic and shaly member. The upper contact of the Shadow Lake Formation is generally gradational with the overlying Gull River Formation (Armstrong and Carter 2006). The formation varies from 0 to 15 m thick and is generally friable and not a potential aggregate source.

The Gull River Formation unconformably overlies the Shadow Lake Formation and consists mainly of limestone, with lesser amounts of dolostone, shale and argillaceous sandstone (Armstrong and Carter 2006). This unit, which is part of the Black River Group, has been subdivided into 3 informal members:

the lower, middle and upper. The upper member of the Gull River Formation consists of light grey to dark brown, thin- to very thick-bedded, bioturbated, fossiliferous limestone. The middle member consists of mainly grey, sparsely fossiliferous lime mudstones that are commonly laminated. The lower member is the most lithologically varied containing light to dark grey to brown, fine-grained dolostones; light grey to dark brown, very fine-grained limestones; green argillaceous sandy dolostones; minor green-grey argillaceous dolomitic sandstone; and green to dark brown shale (Armstrong and Carter 2006). The lower member is often capped by a green argillaceous dolostone informally referred to as the “green marker bed”. The Gull River Formation ranges in thickness in Ontario from 7.5 to 136 m and is a valuable rock formation in the production of aggregate material.

The Gull River Formation is conformably overlain by the Bobcaygeon Formation. The Bobcaygeon Formation is divided into 3 informal members: the lower, middle and upper. The lower member of the Bobcaygeon Formation corresponds stratigraphically to the Coboconk Formation, which is the uppermost unit of the Black River Group (Armstrong and Carter 2006). The lower member consists of light grey-tan to brown-grey, medium- to very thick-bedded, fine- to medium-grained, bioclastic limestones, wackestones, packstones and grainstones.

The middle and upper members of the Bobcaygeon Formation correspond to the lower and upper members of the Kirkfield Formation of the Trenton Group (Armstrong and Carter 2006). The middle member consists of thin- to medium-bedded, bioclastic, very fine- to fine-grained limestones with green shale interbeds and partings. The upper member consists of fine- to medium-grained, dark grey to light brown, thin- to medium-bedded, bioturbated, fossiliferous limestones, ranging from bioclastic wackestones to packstones and grainstones. Shale content is limited to thin shaly partings (Armstrong and Carter 2006). The contact between the 2 members is gradational (Armstrong and Carter 2006). The Bobcaygeon Formation ranges in thickness from 7 to 87 m and has a long history of use by the aggregate industry.

The Bobcaygeon Formation is conformably overlain by the Verulam Formation. The Verulam Formation corresponds stratigraphically to the Sherman Fall Formation of the Trenton Group. The Verulam Formation consists of interbedded limestones and shale which have been divided into an upper and lower member (Armstrong and Carter 2006). The lower member, ranging from 23 to 68 m in thickness, consists of interbedded dark grey to grey, fossiliferous, fine- to coarse-grained limestone and green shale. The upper member is a medium- to coarse-grained, buff to tan coloured, cross-bedded, bioclastic limestone, ranging from 2 to 9 m in thickness. Although generally unsuitable for the production of high-quality aggregate because of the high shale content, the Verulam Formation can be used for the production of Portland cement.

## **BEDROCK RESOURCES**

Precambrian bedrock may exhibit wide variations with respect to aggregate quality over relatively short distances. Consequently, any site proposed for quarry development should be tested in detail before extraction occurs. Highly weathered, brittle and friable Precambrian bedrock, which is unacceptable for aggregate use, may occur in the report area. There are also areas underlain by more massive, hard and durable rock, which appears suitable for a variety of aggregate applications. However, some of the massive, coarse-grained felsic igneous rocks and gneisses with high mica, feldspar and quartz contents may have bonding problems because the smooth cleavage and fracture surfaces of these minerals hinder the adhesion of asphalt and cement mixes. This problem may be circumvented by weathering the rocks for a period of time in stockpiles or by adding chemicals (anti-stripping agents) that erode the smooth surfaces and allow better adhesion. Rogers (1985) reports that some granitic rocks can react slowly with alkalis from Portland cement resulting in premature concrete deterioration.

Of the Paleozoic rock formations that underlie the county, the Gull River and Bobcaygeon formations are best suited for aggregate extraction and production. The soft and friable shales, siltstones, sandstones and conglomerates of the Shadow Lake Formation are unsuitable for most aggregate use. The Verulam Formation can be used in the production of some aggregate products, although the high shale content of this formation limits its use and specialized production methods would be required. As stated earlier, the Verulam Formation can be used to produce cement.

Crushed stone from the Gull River Formation is extracted for a variety of aggregate uses in southern Ontario, including concrete, asphalt, and granular base. Detailed site-specific testing of the rock is necessary because certain beds within the formation are chemically reactive with Portland cement mixes (Rogers 1985; Ryell et al. 1974). The alkali-carbonate reaction can result in the premature deterioration of concrete structures particularly those subject to weather and road salt. Alkali-carbonate reactive beds cannot be readily identified through visual examination in the field. Subjecting the rock to concrete expansion testing, microscopic examination and/or chemical analysis can identify the reactive beds (Rogers 1985; Ryell et al. 1974). Selective extraction of the nonreactive beds may be required for production of concrete aggregates. Ryell et al. (1974) suggest a dilution ratio of 4:1 (competent rock to alkali-reactive rock) may also provide an acceptable solution. The Gull River Formation is generally well suited for use as hot-laid asphalt, but polishing of the stone may be a problem if the rock is used for asphaltic surface course. Beds of shaly, silty to sandy dolostone may require blending with the surrounding, more competent bedrock units for production of granular base. Similarly, beds of calcitic dolostone at the base of the formation may only be suitable for granular base.

Certain beds within the Bobcaygeon Formation may also be alkali-reactive. In this case, an alkali-silicate reaction occurs between Portland cement and the silica-bearing rock strata. Reactive beds within the Bobcaygeon Formation usually contain less than 3% black chert along with microscopic chalcedony (Rogers 1985). The shalier middle parts of the formation may not be as suitable for the production of concrete aggregate as the surrounding strata. As a result, selective extraction measures may be required for the production of concrete aggregate within the formation. The formation is generally well suited for most other aggregate uses including asphaltic stone and granular base.

Bedrock samples were collected over the course of this study and have been submitted to the Ministry of Transportation for standard aggregate testing. The results of these tests will be added to a spreadsheet that is used to provide test result averages on a long-term, on-going basis.

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# 20. Project Unit 09-023. Aggregate Resources Inventory of Frontenac County, Southern Ontario

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## INTRODUCTION

Field investigations were conducted during the summer of 2009 to complete an aggregate resources assessment for Frontenac County, southeastern Ontario. Field work included site visits to active pits and quarries, general field observations of glacial deposits and potential bedrock aggregate resources.

Frontenac County is located on the north shore of Lake Ontario and occupies an area close to 4000 km<sup>2</sup>. The study area is covered by National Topographic System (NTS) map sheets 31 C/1, 31 C/8 to C/11, 31 C/14, 31 C/15, and 31 F/2 and 31 F/3. It is inhabited by more than 140 000 residents (Statistics Canada 2007) (Table 20.1). Much of the county is rural, with access being through Highways 401 and 10, and Sydenham and Perth roads, as well as other municipal and county roads (Figure 20.1). The county is divided into 5 lower tier municipalities, with Kingston being the county's largest city and host to many of the county's services.

## BEDROCK GEOLOGY

The bedrock geology of Frontenac County is dominated by Precambrian metamorphic and plutonic rocks of the Canadian Shield (Kingston, Papertzian and Williams 1985; Ministry of Natural Resources 1987; Ontario Geological Survey 1991). These rocks are highly folded and faulted, with folds generally oriented northeast. Due to the high variability in lithologies, these rocks require site-specific testing to evaluate their potential as aggregate sources and are, therefore, not considered further at this time.

The Precambrian bedrock is overlain by several Paleozoic units ranging in age from the Cambrian to Middle Ordovician (Williams, Wolf and Rae 1984; Russell and Williams 1985a-f). These bedrock formations crop out in the southern townships and are most continuous in the southwestern part of the county.

**Table 20.1.** Municipalities within Frontenac County, aerial extent and population (Statistics Canada 2007).

<b>Municipality</b>	<b>Area (km<sup>2</sup>)</b>	<b>Population</b>
Central Frontenac	970	4665
Frontenac Islands	170	1862
Kingston	450	117 207
North Frontenac	1135	1904
South Frontenac	941	18 227
<b>Total</b>	<b>3666</b>	<b>143 865</b>

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*Summary of Field Work and Other Activities 2009,  
Ontario Geological Survey, Open File Report 6240, p.20-1 to 20-9.*

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The oldest Paleozoic bedrock formation in the study area is the Cambrian Covey Hill Formation. This unit consists of interbedded noncalcareous feldspathic conglomerate and impure sandstones, and occurs in a limited outcrop near the east-central boundary of the county (Carson 1981; Armstrong and Carter 2006; Armstrong and Dodge 2007) (Figure 20.2). The Covey Hill Formation has the potential to be quarried for aggregate, but no extraction of this formation is occurring in Frontenac County.

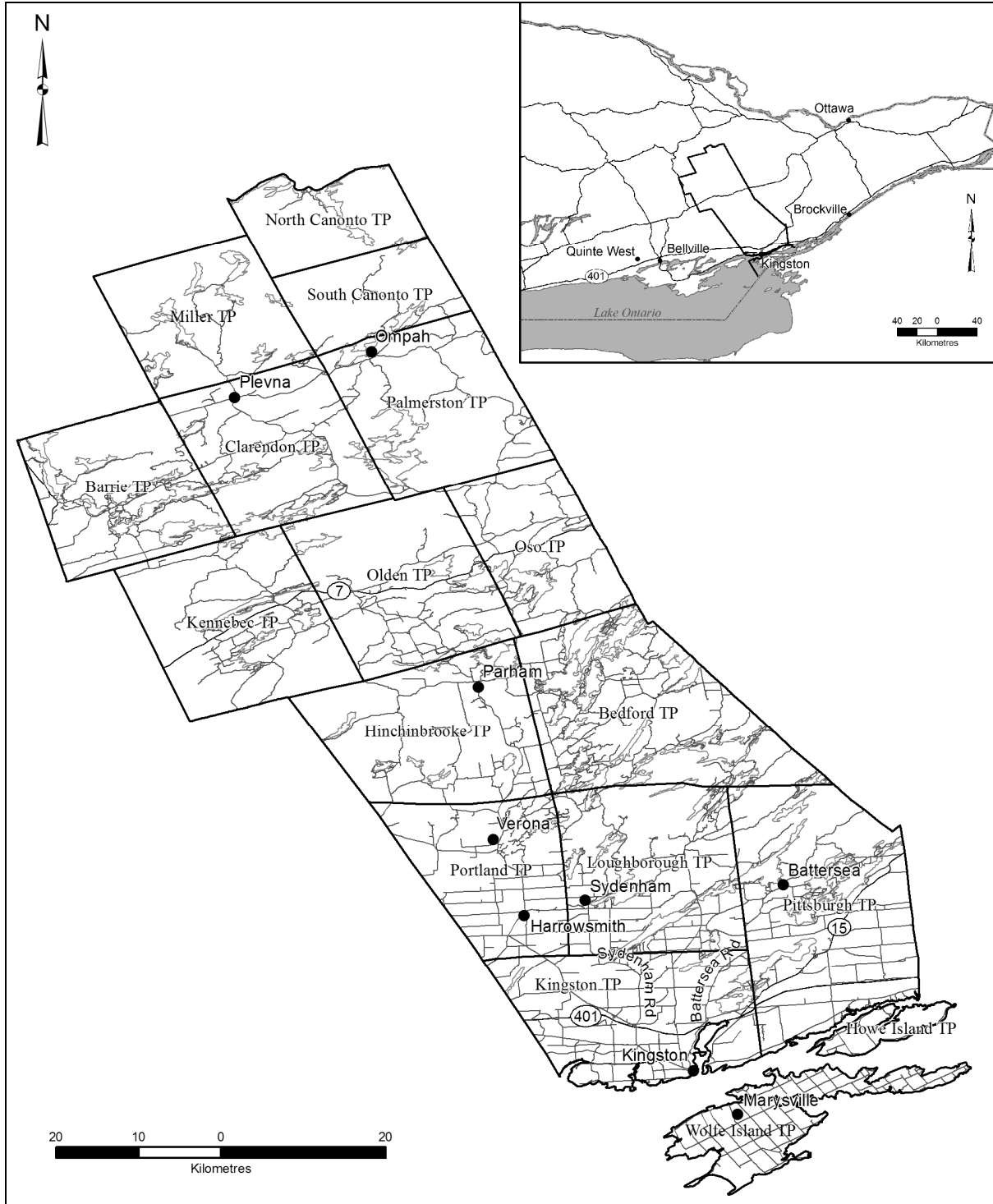


Figure 20.1. Location map of the study area.

The Cambro-Ordovician Nepean Formation is a thin- to massive-bedded quartz sandstone with some conglomerates, and rare shaley partings (Carson 1981, 1982a, 1982b; Armstrong and Carter 2006). This unit crops out primarily in southeast Frontenac County, but small outcrops exist in Loughborough and Portland townships (see Figure 20.2). This formation is extracted for dimension stone, but has been found to be alkali-reactive when used in Portland cement (Derry Michener Booth and Wahl and Ontario Geological Survey 1989; Jagger Hims Limited and Ontario Geological Survey 1999).

The Shadow Lake Formation is a silty, sandy dolostone containing shale partings and minor interbeds of sandstone. Minor scattered outcrops of this formation occur in Portland, Loughborough and Pittsburgh townships (see Figure 20.2) (Carson 1981, 1982a; Armstrong and Carter 2006; Armstrong and

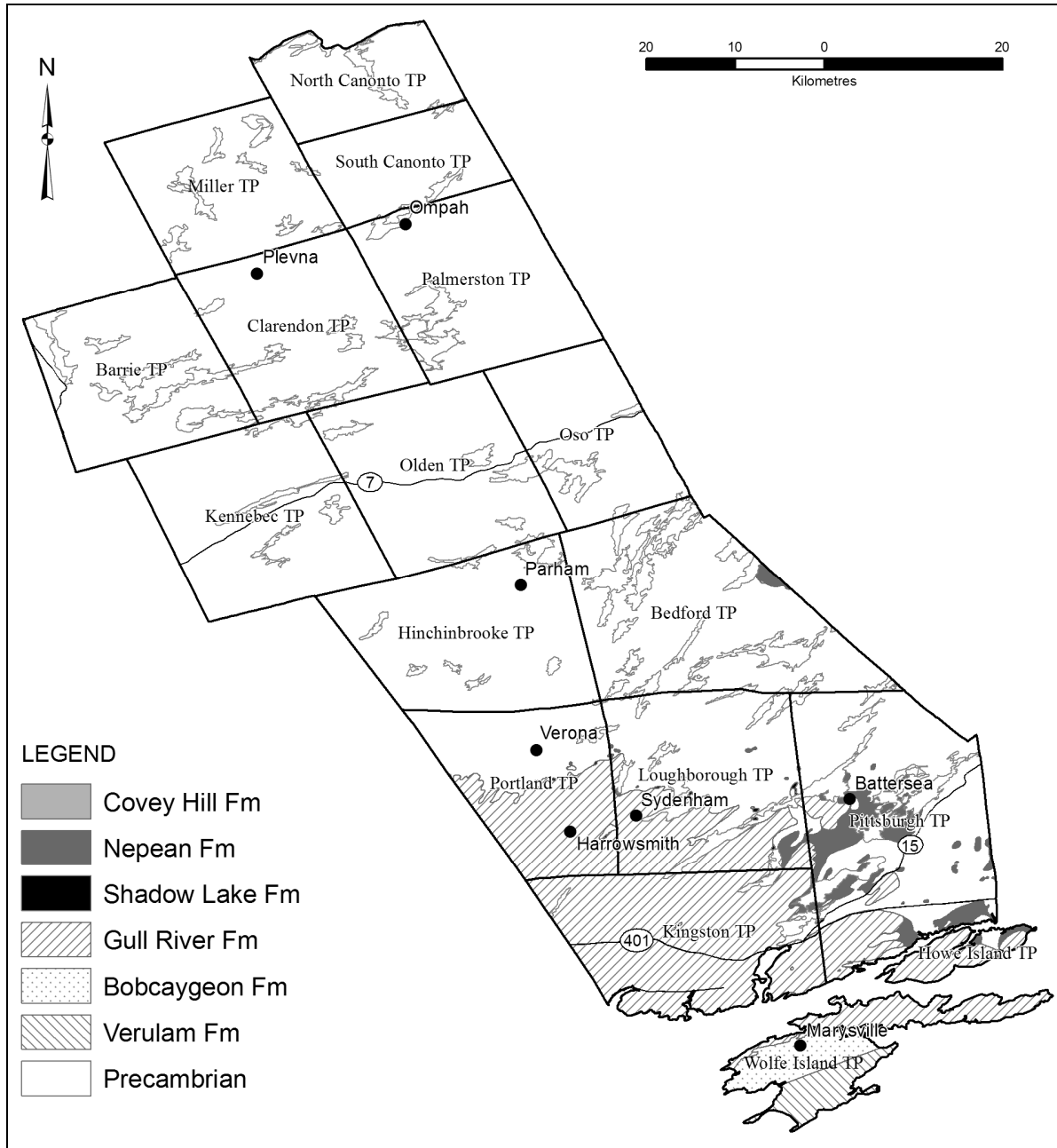


Figure 20.2. Simplified bedrock geology of Frontenac County (after Armstrong and Dodge 2007).

Dodge 2007). This bedrock unit has been used for decorative stone in the past, but is of very limited value as an aggregate source (Derry Michener Booth and Wahl and Ontario Geological Survey 1989; Jagger Hims Limited and Ontario Geological Survey 1999).

The Gull River Formation consists of interbedded silty dolostone, lithographic to fine-crystalline limestone, shale and fine-grained calcareous quartz limestone (Carson 1981, 1982a, 1982b; Armstrong and Carter 2006). Some beds within this formation contain alkali-reactive dolostone beds and some chert nodules. The Gull River Formation is the most extensive Paleozoic unit within Frontenac County and occurs in the southeastern townships, Howe Island and northeast Wolfe Island (*see* Figure 20.2). The formation is quarried for granular course aggregate, building stone and concrete sand.

The Middle Ordovician Bobcaygeon Formation consists of thin- to thick-bedded, fossiliferous limestone with shaley partings and some locally significant shale interbeds (Armstrong and Carter 2006; Armstrong and Dodge 2007). This formation occurs in central Wolfe Island and can be quarried for crushed stone, granular base course aggregate (*see* Figure 20.2) (Carson 1982a). Some beds may be alkali-reactive in Portland cement.

The Verulam Formation is a fossiliferous, pure to argillaceous limestone, interbedded with calcareous shale (Armstrong and Carter 2006). The formation occurs in southeast Wolfe Island (Carson 1982a) (*see* Figure 20.2). The formation has been quarried for aggregate in the past, but shale beds may be problematic for widespread extraction (Derry Michener Booth and Wahl and Ontario Geological Survey 1989; Jagger Hims Limited and Ontario Geological Survey 1999).

## PHYSIOGRAPHY AND SURFICIAL GEOLOGY

The landscape of Frontenac County varies from rough to rounded bedrock knobs to flat undulating plains. The county has been divided into 4 physiographic regions: the Algonquin Highlands, the Georgian Bay Fringe, the Napanee Plain, and the Leeds Knobs and Flats (Chapman and Putnam 1984a).

The largest physiographic region in Frontenac County is the Algonquin Highlands, which occupies the northern and east-central portion of the county (Figure 20.3). This region is characterized by rough rounded knobs and hills of Precambrian bedrock. Glacial drift is thin in this region, and bedrock outcrops occur frequently. The valleys between bedrock highs are floored with outwash sand and gravel, and commonly filled with bogs or swamps (Chapman and Putnam 1984a).

The Georgian Bay Fringe separates the northern and central reaches of the Algonquin Highlands in Frontenac County. This physiographic region is characterized by shallow soil and Precambrian bedrock knobs and ridges. Minor tracts of glaciofluvial and ice-contact deposits occupy some of the valleys within this region (Chapman and Putnam 1984a).

The Napanee Plain physiographic region occupies southwest and south-central Frontenac County. This region is characterized by flat to undulating limestone with most of the overburden in the area having been removed by glacial activity. Some thicker drift occurs in stream valleys, and depressions often have shallow deposits of stratified clay (Chapman and Putnam 1984a).

The Leeds Knob and Flats physiographic region is the smallest region in Frontenac County and occupies its southeast corner. This region is characterized by knobs of Precambrian granite and flat-lying clay plains that were deposited by glacial lakes occupying the Lake Ontario basin. Wave action in these lakes removed any thin sediment cover overlying the bedrock knobs (Chapman and Putnam 1984a).

During the Last Glacial Maximum (~20 000 ka BP) the Laurentide Ice Sheet occupied all of Frontenac County and extended into New York State. Ice advanced across the study area from the northeast to the southwest, which is evidenced by striated bedrock surfaces and ice flow indicators within the glacial sediments. In the northern part of the county, the ice scoured, polished and rounded the bedrock hills, removed much of the surficial material; later sediments were deposited in bedrock lows as glaciofluvial and ice-contact deposits (Figure 20.4) (Henderson 1966, 1973a, 1973b; Henderson and Kettles 1992; Kettles 1992; Kettles, Henderson and Henderson 1992; Leyland and Russell 1983, 1984; Ontario Geological Survey 2003; Barnett 1992).

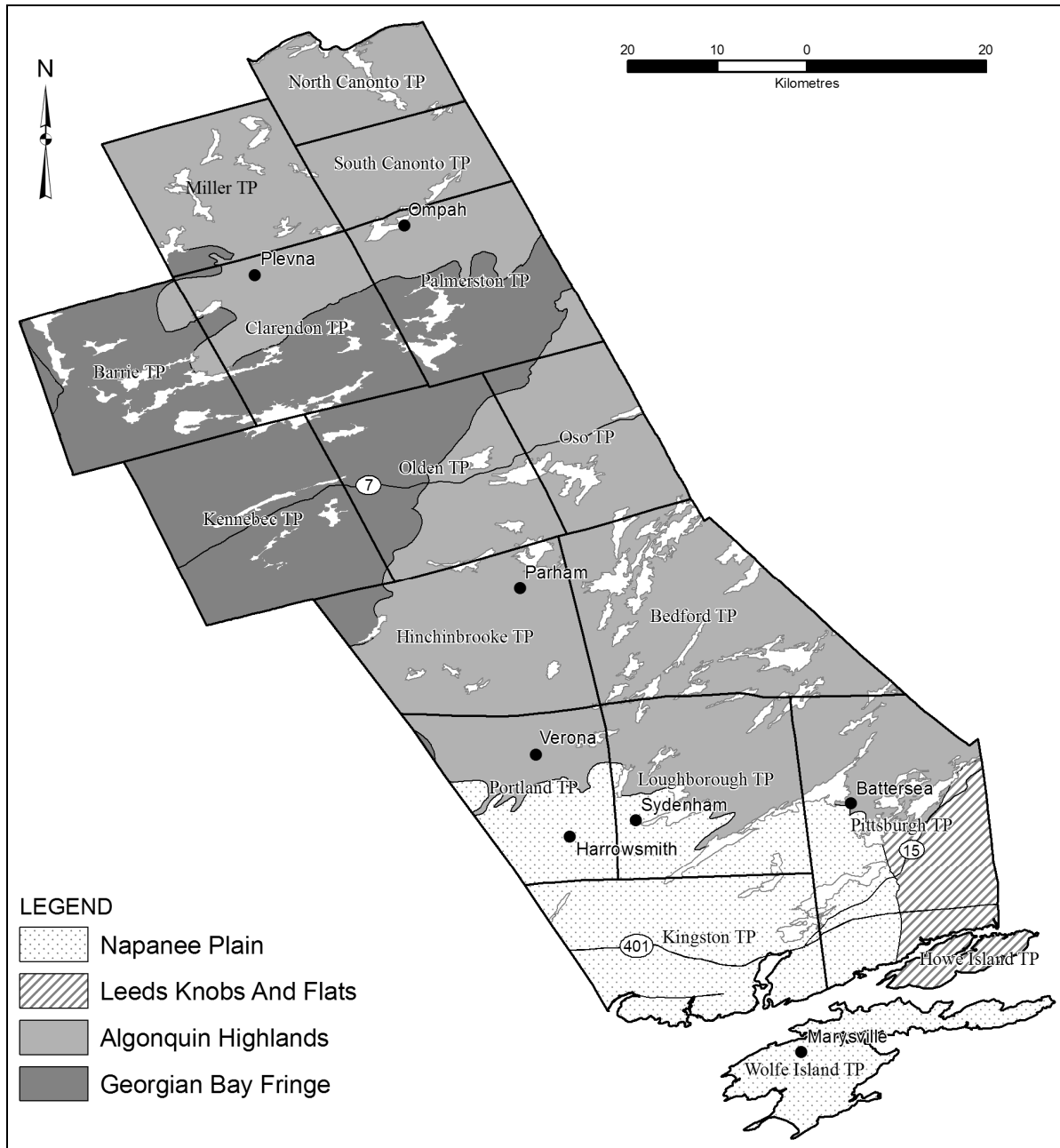
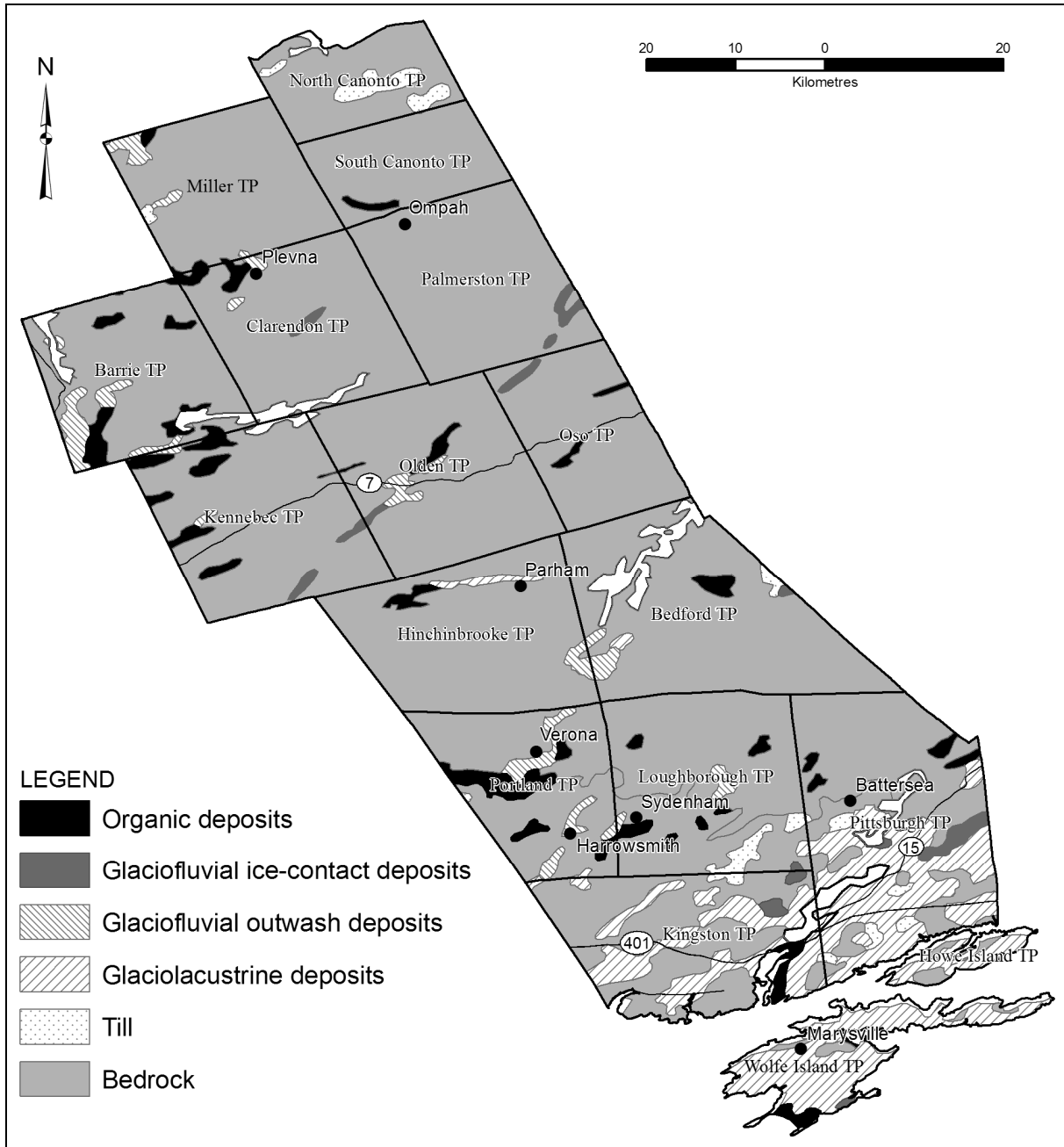


Figure 20.3. Physiographic regions of Frontenac County (from Chapman and Putnam 1984b).

As the Laurentide Ice Sheet retreated, southern Frontenac County was dominated by glaciolacustrine and ice-contact processes leaving large tracts of fine-grained sediments in broad, flat plains as well as beach and deltaic sands and gravels.

## METHODS

Prior to beginning field work, a compilation of previously published maps and reports pertaining to aggregate resources within Frontenac County was completed. The seamless surficial geology map of southern Ontario (Ontario Geological Survey 2003) was used to identify potential sand and gravel deposits.



**Figure 20.4.** Simplified surficial geology of Frontenac County (after Ontario Geological Survey 2003).

Water-well records were obtained from the Ministry of the Environment (MOE) and geotechnical borehole logs were provided by the Ministry of Transportation (MTO). These data, along with additional sample and testing results, were consulted to determine target areas for field research.

Field work was undertaken to ground truth the boundaries of granular deposit as well as to assess their depth and quality. Potential bedrock resources were assessed by examining quarries and rock outcrops.

## **AGGREGATE POTENTIAL**

Aggregate resources in Frontenac County consist of Paleozoic limestones and dolostones and scattered glaciofluvial and ice-contact sand and gravels.

The Gull River and Bobcaygeon bedrock formations are quarried for crushed aggregate and building stone in southern Frontenac County. There are currently 28 active quarry licences in the study area.

Sand and gravel deposits commonly occupy valleys between bedrock ridges and knobs. The gravel and silt content of these deposits vary considerably and, in some cases, crushing and screening or washing of the material may be required. The deposits range from clast free outwash sands to cobble gravels; higher quality granular aggregates are commonly associated with ice-contact eskers, kame and deltaic deposits. Granular material is extracted throughout the county, mostly for local use in road construction and maintenance.

## **SUMMARY**

The aggregate resources mapping of Frontenac County is ongoing. Data collected in the field will be used to complete sand and gravel as well as bedrock aggregate resource maps for the county, which will be made available in both paper and digital formats.

## **ACKNOWLEDGEMENTS**

The author wishes to acknowledge Cameron MacDougall, whose assistance ensured a successful summer field season. Landowners and pit operators are also thanked for their co-operation and granting the field party access to their properties.

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# 21. Project Unit 06-024. A Progress Report on Subsurface Mapping in the Brantford–Woodstock Area, Southwestern Ontario

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## INTRODUCTION

A project of three-dimensional (3D) mapping of Quaternary deposits in the Brantford–Woodstock area of southwestern Ontario (Figure 21.1) is entering its final phase with the completion of field components during the 2006–2008 field seasons and block model construction in 2009. This project is one of several that are currently being undertaken as part of the Ontario Geological Survey (OGS) groundwater mapping program. Similar studies have been completed previously within the Regional Municipality of Waterloo (Bajc and Shirota 2007) and are currently ongoing within the Barrie–Oro and the Orangeville areas (Burt 2007, 2008).

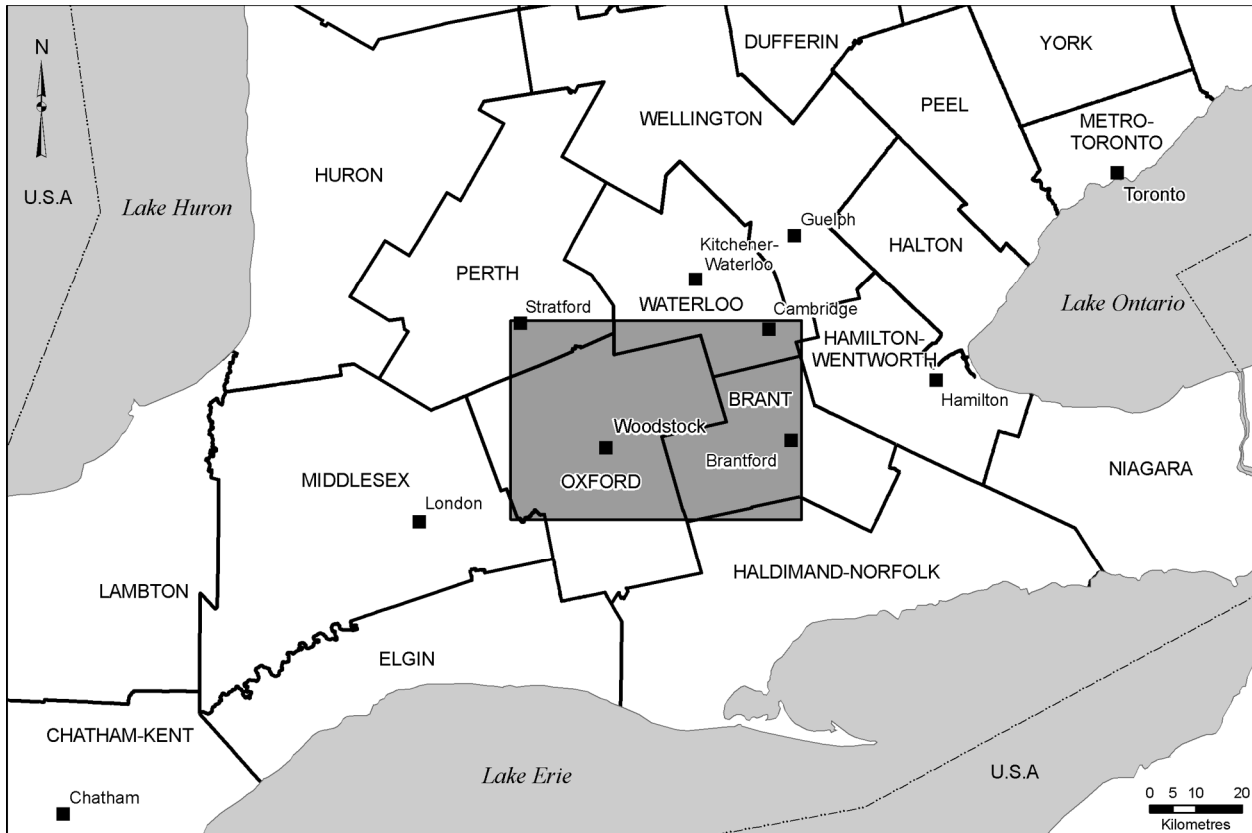


Figure 21.1. Location of the Brantford–Woodstock project area in southwestern Ontario.

*Summary of Field Work and Other Activities 2009,  
Ontario Geological Survey, Open File Report 6240, p.21-1 to 21-4.*

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The objectives of these projects are to develop interactive 3D models of Quaternary geology that can 1) aid in studies involving groundwater extraction, protection and remediation; 2) assist with the development of policies surrounding land use and nutrient management; and 3) help to better understand the interaction between ground and surface waters. An understanding of the distribution and character of aquifers and confining aquitards will assist with the development of source water protection plans and a geoscience-based management plan for the groundwater resource.

## **SUMMARY OF FIELD PROGRAMS**

Field activities commenced in the fall of 2006 and consisted of a reconnaissance program of Quaternary geology whereby all available exposures within the study area were logged and entered into a database of subsurface geology (Bajc 2006). Following the 2006 field season, this database was populated with the records of Ministry of the Environment water wells, Ministry of Transportation geotechnical records (GEOCRETS) and depth-to-bedrock information contained within Ministry of Natural Resources oil and gas database. To date, this database contains in excess of 15 000 records.

During the 2007 and 2008 field seasons, 36 continuously cored boreholes were drilled across the study area to develop a stratigraphic framework for the modelling exercise and to assist with the interpretation of low-quality water well records which account for a significant proportion of the subsurface database. Details of these drilling programs and the stratigraphic records observed can be found in Bajc (2007, 2008).

As part of the Dundas buried valley project, a project being undertaken jointly between the OGS and the Grand River Conservation Authority (Zwiers, Rainsford and Bajc 2008), 4 additional continuously cored holes were completed in the northeastern corner of the Brantford–Woodstock area. These cores were transported to Sudbury and logged and sampled in detail during the spring of 2009.

## **BLOCK MODELLING**

Datamine Studio<sup>®</sup> Software (Version 3.18.2751.0) continues to be used at the OGS as the software package for the interpretation of subsurface information and the generation of a three-dimensional block model of hydrostratigraphic units. A conceptual model consisting of 20 hydrostratigraphic units similar to that developed for the Waterloo area to the north (Bajc and Shirota 2007) was employed for this survey. The main advancement in the modelling process since the release of the Waterloo survey was the incorporation of data quality into the geostatistical process of layer interpolation. Water well records were assigned a data quality of “Low”. Non-cored geotechnical and hydrogeological borings were assigned a data quality of “Medium” and cored boreholes and surface exposure logs were attributed with a data quality of “High”. A minimum of 3 medium- to low-quality picks, 2 medium-quality picks or 1 high-quality pick for a particular hydrostratigraphic unit were required within a predefined search radius to model that layer within the search radius. By employing this feature, the records of higher quality boreholes were preferentially honoured resulting in more continuous surfaces in areas of sparse data. Construction of the 3D block model is in the validation stage. Over 42 000 picks have been generated to date.

## OBSERVATIONS ON GEOLOGY

A number of preliminary observations are possible based on the interim block model for the Brantford–Woodstock area produced to date. The elevation of the bedrock surface declines from a high of 325 m asl in the northwest corner of the study area to a low of 150 m in the southeast. The Dundas buried valley (or trough) and the Onondaga Escarpment form first-order topographic elements of the bedrock surface. Second-order depressions, some of which are linear in nature, ornament the bedrock surface throughout. Drift thickness ranges between 0 and 115 m with the thickest deposits located in the Waterloo and Lakeview moraines, within a large upland south of Woodstock and within a series of Erie lobe recessional moraines, the most notable of which are the Ingersoll, Paris and Galt moraines.

Deposits predating Catfish Creek Till (i.e., Canning drift and older tills and stratified deposits greater than 25 000 years old) are widespread yet discontinuous throughout the study area. They occur primarily west of the Norwich Moraine, a prominent, north-trending, Erie lobe ice-marginal feature. Catfish Creek Till occurs over a similar geographic extent, yet is far more continuous with the thickest deposits (62 m) occurring over the western third of the study area as well as beneath the Waterloo Moraine. Postglacial incision along the Thames and Grand River valleys has, to a large extent, removed great thicknesses of Catfish Creek drift and older deposits. Port Bruce Phase deposits are represented by discontinuous deposits of sand and gravel sandwiched between both Huron and Erie lobe fine-grained deposits (diamicton and glaciolacustrine deposits). The most significant deposits of sand and gravel form important aquifers and occur within the Waterloo and Lakeside moraines as well as a large, buried glaciofluvial system south of Woodstock. Water well records suggest that the large deposits of sand and gravel just south of Woodstock along Highway 401 are up to 80 m thick. Modest thicknesses of 40 to 60 m are common within the Lakeside and Waterloo moraines. Notable accumulations of sand and gravel have also been identified along the trend of the Tillsonburg Moraine. With the exception of parts of the Waterloo and Lakeside moraines, Port Bruce Phase tills (Tavistock and Port Stanley tills) and associated stratified deposits form a fairly continuous impermeable blanket over most of the study area. The thickest accumulations occur along the southern parts of the Ingersoll Moraine where up to 58 m of sediment has been documented. Grand River outwash deposits form a distinct south-trending belt along the eastern margin of the study area bordered on the west by the Norwich Moraine and extending eastward beneath Wentworth Till along the trends of the Paris and Galt moraines. Grand River outwash deposits generally become fine textured to the south where they become deltaic and lacustrine in nature. Sandy deposits within this area comprise the northern part of the Norfolk sand plain physiographic region. Stratified deposits that accumulated along the Paris and Galt ice margins are included in this unit and reach modelled thicknesses of up to 67 m in places. Wentworth Till occurs primarily along the Paris and Galt moraines and is generally thicker to the north where thicknesses of 50 m have been modelled. East of the Galt Moraine, the stratigraphic sequence changes drastically becoming almost entirely a postglacial, glaciolacustrine succession. Thin deposits of regressive sands generally cap a thick sequence of massive to rhythmically laminated silts and clays that are up to 69 m thick. Thin, discontinuous deposits of Wentworth Till rest directly on bedrock beneath the glaciolacustrine sediments.

## RADIOCARBON DATING

A number of sites (20) containing deeply buried organic remains have been discovered within the study area. Many of these sites contain fossil material suitable for radiocarbon dating that has not only helped to refine geochronology, but has provided insights into the paleoenvironments present during the nonglacial interval(s).

The fossiliferous units occur mostly either beneath or within Nissouri Phase Catfish Creek drift and comprise thin (<2 to 3 m) units of waterlain sediment with detrital plant and animal fossils (insects, molluscs, ostracodes, bones/teeth, seeds, leaves, etc.) and well-preserved pollen. Reddish glaciogenic deposits, derived from the Erie–Ontario lake basins, likely correlatable to Canning drift, underlie most of the organic sequences. In a few instances, associated deposits display pedogenic features suggesting a possible weathering interval. Accelerator mass spectrometry (AMS) radiocarbon analyses on wood samples range in age from 26.3 to 50.5 ka BP and include 2 dates reported as >47 ka BP (18 dates on 9 sites). Most of these deposits are assigned to the Elgin Subepisode (formerly Middle Wisconsinan).

Fossil remains have also been recovered from sandy glaciolacustrine deposits between both Port Stanley and Catfish Creek tills (Erie Phase) and Wentworth and Port Stanley–Catfish Creek tills (Mackinaw Phase). AMS radiocarbon ages of between 30.8 and 48.4 ka BP have been obtained on wood from 5 localities. These dates are considered significantly older than the sediments containing them and suggest significant reworking of older deposits.

Most fossils are, therefore, probably not in-situ and are thought to represent material either transported long-distances via wind, water and ice, reworked from other environments or originating from deposits of different ages. The fossils suggest the existence of a mix of treeless, open parkland, and more forested landscapes, along with localized aquatic habitats (stream, riverine and wetlands of several kinds), which further indicates the possibility that the fossils were brought together by chance at the depositional sites. Together, the fossil assemblages imply a typical cool interstadial climate.

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# 22. Project Unit 08-003. The Orangeville Moraine Project: An Update of Field Activities

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## INTRODUCTION

In 2008, the Ontario Geological Survey (OGS), with the co-operation of the Nottawasaga Valley Conservation Authority (NVCA), the Grand River Conservation Authority (GRCA) and the Credit Valley Conservation Authority (CVCA), launched the fourth in a series of highly successful, regional-scale, three-dimensional (3D) surficial mapping projects for groundwater applications. As with previous studies, key objectives of the Orangeville Moraine Project are

1. the reconstruction of the Quaternary history of the Orangeville Moraine;
2. the development of a 3D model of Quaternary sediments, and
3. the characterization of the properties of the modelled sediment packages.

The surficial geologic model will be based on the interpretation of natural and manmade exposures, existing drill records (water wells, geotechnical drilling, etc.) and new drilling. It is anticipated that the final block model of Quaternary deposits will be used by public agencies and other client and stakeholder groups for several different purposes: studies involving groundwater recharge, exploration, extraction, protection and remediation; studies to support the *Clean Water Act*; detailed planning for healthy community growth (*Places to Grow Act*); development of policies surrounding land use and nutrient management; and enhanced understanding of the interaction between ground and surface waters.

## STUDY AREA LOCATION

The study area encompasses approximately 1550 km<sup>2</sup> centred on the Orangeville Moraine and extends from the Waterloo Region to north of Orangeville (Figure 22.1). Portions of the County of Dufferin (Township of East Luther Grand Valley, Township of Amaranth, Town of Mono, Town of Orangeville and the Township of East Garafraxa), the County of Wellington (Township of Wellington North, Township of Mapleton, Township of Centre Wellington, Town of Erin and the Township of Guelph–Eramosa), the Regional Municipality of Peel (Town of Caledon) and the Regional Municipality of Halton (Town of Halton Hills and Town of Milton), represented on 1:50 000 scale National Topographic System (NTS) map sheets 40 P/09 and 40 P/16, are included within the study area. The town of Orangeville is the largest urban centre within the study area. The communities of Acton, Alton, Belwood, Elora, Erin, Fergus, Grand Valley, Hillsburgh and Rockwood, as well as numerous smaller hamlets, are also located within the study area.

Key elements of the regional setting including bedrock geology, drift thickness, physiography, surficial geology and surface drainage were briefly described in a previous report (Burt 2008).

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*Summary of Field Work and Other Activities 2009,*  
*Ontario Geological Survey, Open File Report 6240, p.22-1 to 22-3.*

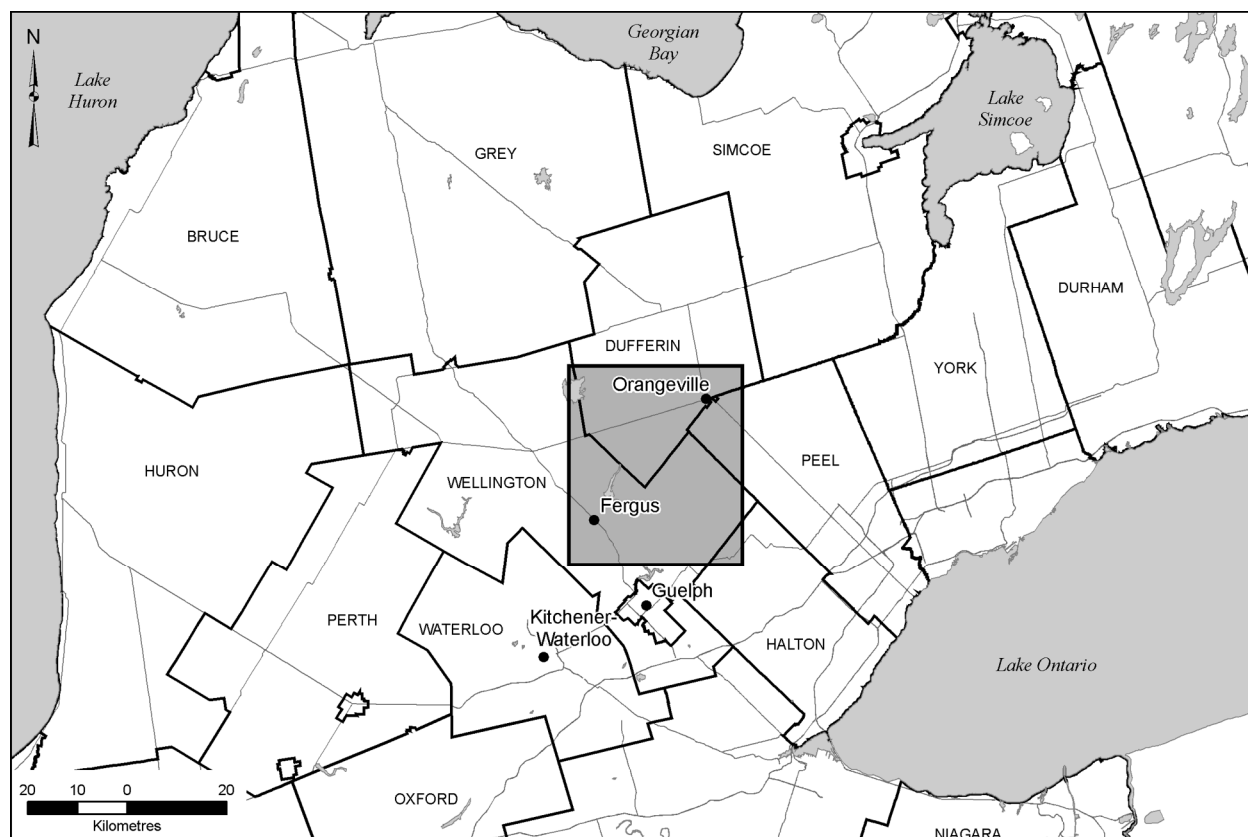
## PROJECT STATUS

The Orangeville Moraine Project was initiated in 2008 with the first in a series of drilling programs targeting the overburden and upper 3 m of competent bedrock. A total of 16 boreholes, totalling 735 m, were drilled in the fall and early winter of 2008. The drilling program focussed on 2 principal objectives of the project:

1. examining the regional stratigraphy in the central and northwestern sections of the study area in order to define the extent and thickness of key regional aquitards including Tavistock Till and Catfish Creek Till, and the associated fine-grained glaciolacustrine sediments.
2. exploring the thickness and properties of the broad central section and southern arms of the Orangeville Moraine within the context of the regional stratigraphy. The Orangeville Moraine has been defined as an important groundwater recharge area; thus, a key goal of this project is to establish whether a regional aquitard extends under the moraine or if the silt, sand and gravel sediments of the moraine are directly connected with the underlying bedrock aquifer.

The second phase of drilling is currently underway and a similar number of holes are planned. This drilling program is focussed on

1. examining the regional stratigraphy of the central and southeastern sections of the study area. Key regional aquitards in this area include Port Stanley, Wentworth and Catfish Creek tills.
2. extending drilling into the northern arms of the Orangeville Moraine.



**Figure 22.1.** Location of the Orangeville moraine study area in southwestern Ontario.

3. establishing the depths and nature of the sedimentary fills of some of the buried bedrock valleys located in the southern and eastern portions of the study area. As with the Orangeville Moraine, it is vital to determine the presence or absence of an aquitard between the silt and sand valley fills and bedrock aquifer system.
4. providing stratigraphic control for the extent and depth of the Paris Moraine sediments between Blue Spring Creek and the Credit River, as well as determining the presence or absence of an underlying regional aquitard. The groundwater recharge potential for the Paris–Galt Moraine system has recently been the subject of increased public awareness as evidenced by 1) an *Environmental Bill of Rights* application to assess policy and planning protection afforded the moraines (Ministry of the Environment 2009) and 2) a Geological Association of Canada field trip with visits to the central area of the moraine system (Russell, Cummings and Sharpe 2009).

To date, monitoring wells have been installed at 4 locations by the local conservation authorities (an overburden well by NVCA, a nested overburden and bedrock well by CVCA and 2 overburden wells by GRCA) with the intention that the wells will form part of the provincial groundwater monitoring system. Any additional drilling in subsequent years will target the re-entrant bedrock valley systems (Hockley River Valley, Credit River Valley and Acton–Black Creek Valley), and additional buried bedrock valleys, as well as filling in data gaps in the regional stratigraphy of the area.

Information obtained during the drilling programs and from the examination of natural and man-made exposures will be used to interpret existing drilling records including water well and geotechnical drilling records. As with previous OGS 3D modelling projects, Datamine Studio<sup>®</sup> Software, a software package developed for the mining industry and adapted for overburden mapping for groundwater modelling applications with a series of scripts, will be used for modelling and the preliminary generation of products (*see* Bajc and Newton (2005) and Burt (2007) for more information on the adaptation of the software using scripts).

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# 23. Project Unit 06-026. Investigation of the Dundas Buried Bedrock Valley, Southern Ontario

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## INTRODUCTION

The Ontario Geological Survey (OGS) and the Grand River Conservation Authority (GRCA) are undertaking a collaborative study of the Dundas buried bedrock valley located in southern Ontario. The Dundas valley is a geological feature that is thought to be a preglacial drainage system (Singer, Cheng and Scafe 2003) incised in bedrock and subsequently infilled with unconsolidated sediments. The Dundas valley is believed to extend from beneath Lake Ontario, through Burlington Bay, and westward toward Lake Huron, traversing the Grand River watershed (Figure 23.1). Portions of the valley are interpreted to underlie the Waterloo, Cambridge and Paris–Brantford areas.

Understanding the feature is considered an important component of defining the groundwater resources within the Grand River watershed. For instance, if the feature is relatively continuous, it may strongly influence groundwater movement at the watershed scale and it may represent an important target for municipal water supplies.

The purpose of this study is to better understand the location of the buried valley channel as well as the geological and hydrogeological character of the infilling sediments. Much of the original understanding of this feature was based on data derived from water-well records, which pose some significant limitations when used for geological interpretation. At the completion of the current study, a more comprehensive conceptual model will be in place. The updated model will be built upon through the 4 phases that comprise this study:

- Phase 1: Data compilation / Preliminary conceptualization
- Phase 2: Geophysical surveying
- Phase 3: Drilling and hydrogeological testing
- Phase 4: Development of conceptual three-dimensional (3D) geologic model

Each phase will conclude with a refinement to the conceptual model to reflect the increased understanding that has been gained. Phase 1 of the study was completed in May 2007, Phase 2 in January 2008, and Phase 3 is currently in progress. For a summary of the results of Phases 1 and 2, the reader is referred to Zwiers, Strynatka and Rainsford (2007) and Zwiers, Rainsford and Bajc (2008).

## RESULTS OF PHASE 3 DRILLING AND HYDROGEOLOGICAL TESTING

The third phase of the investigation consists of an overburden drilling program in 3 priority areas followed by hydrogeological testing of the target aquifers. Details on the priority areas selection process

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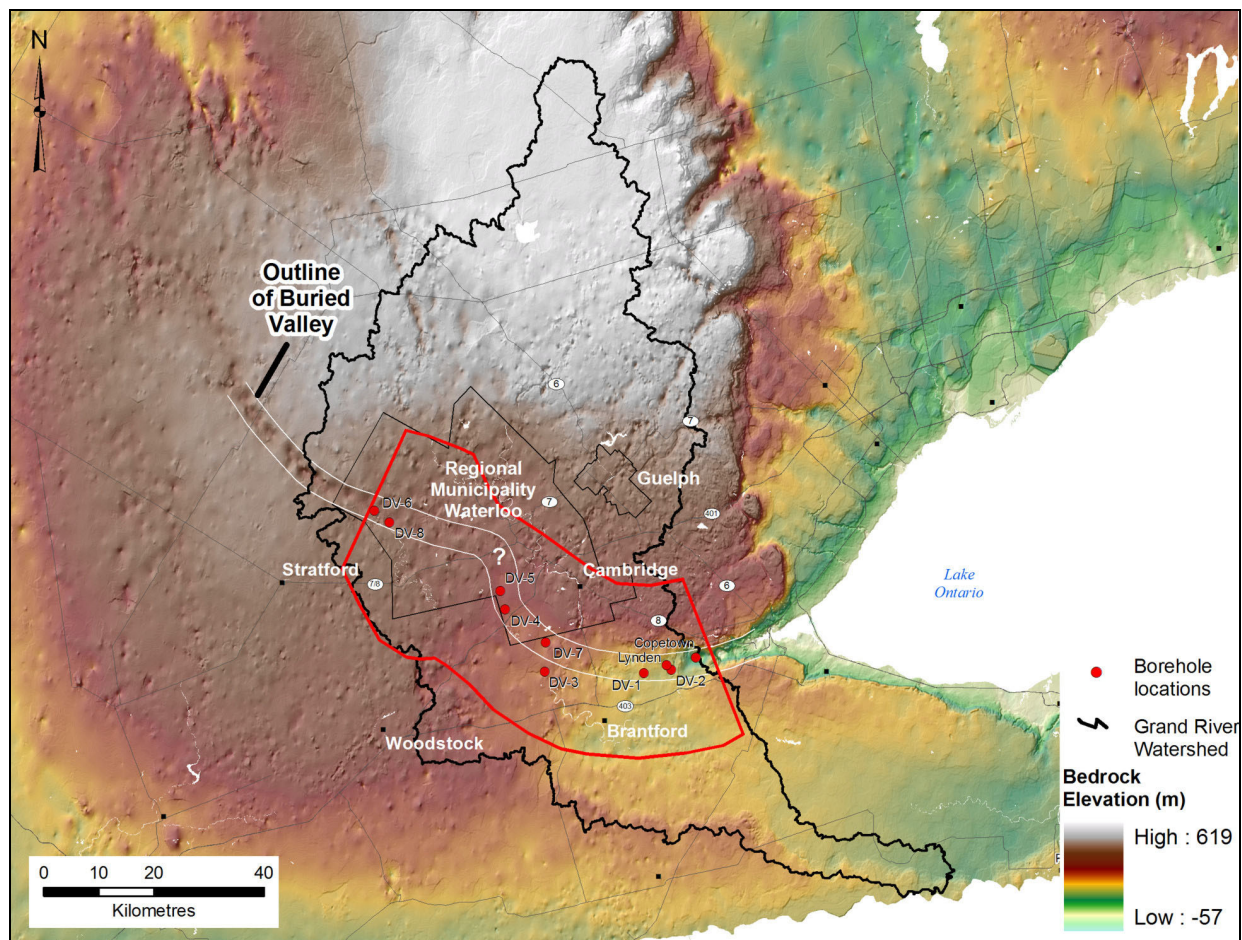
*Summary of Field Work and Other Activities 2009,  
Ontario Geological Survey, Open File Report 6240, p.23-1 to 23-7.*

can be found in Zwiars, Rainsford and Bajc (2008). The areas identified as highest priorities are illustrated in Figure 23.2 and consist of

1. an east-trending section of the valley extending from just north of the town of Paris to the community of Lynden;
2. a north-trending section of the feature extending from the southwest side of Kitchener to south of Highway 401 between Ayr and Roseville; and
3. a northwest-trending section of the buried valley extending from just north of Wellesley southeast to approximately the intersection of Hackbart Road and Gerber Road

A total of 8 locations were selected for drilling within the priority areas. Drilling occurred in late 2008 and early 2009 using a track-mounted rig using a PQ coring system. Over 600 m of PQ size (85 mm) core was recovered from 8 boreholes with depths ranging between 45 and 107 m. In all cases, the entire overburden sequence was cored and coring was terminated once 2 to 3 m of competent bedrock had been recovered.

Core recovery was excellent with a program average of 87%, although recovery in coarser grained sections (cobble gravel and loose, stony till) was occasionally problematic. A preliminary geologic log was obtained in the field. The core was sealed in polyvinyl chloride (PVC) tubes and shipped to the Ontario Geological Survey (Willet Green Miller Centre, Sudbury), where it was photographed, logged and sampled in detail for particle size and carbonate content.



**Figure 23.1.** Location of the Dundas buried bedrock valley study area (red line) in southern Ontario.

Monitoring wells were installed at each drill site using 6.25 cm inside diameter schedule 40 PVC pipe. In most cases, the monitoring wells were screened in coarse-grained units fairly close to the bedrock surface and they were isolated from units stratigraphically higher or lower using bentonite seals.

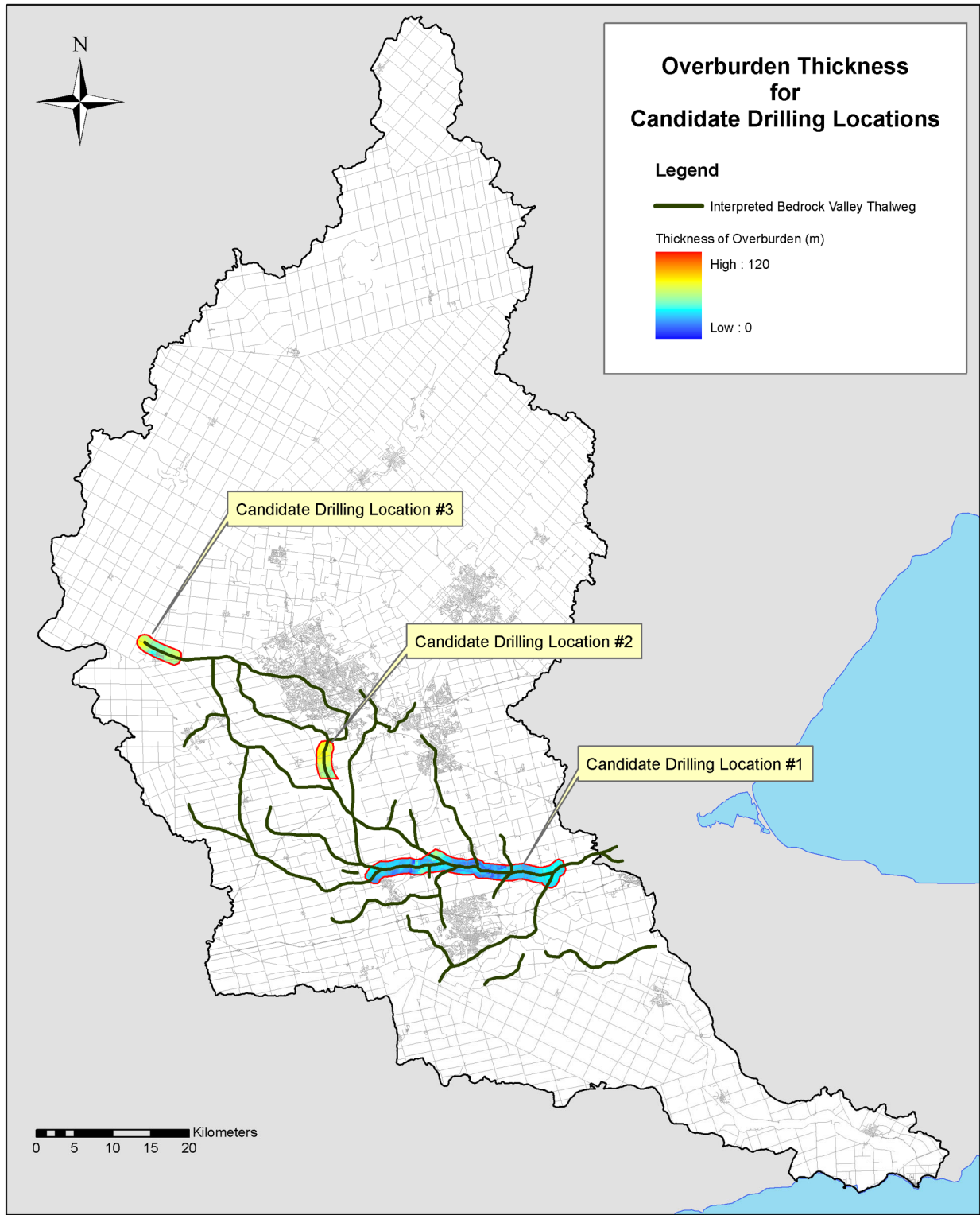
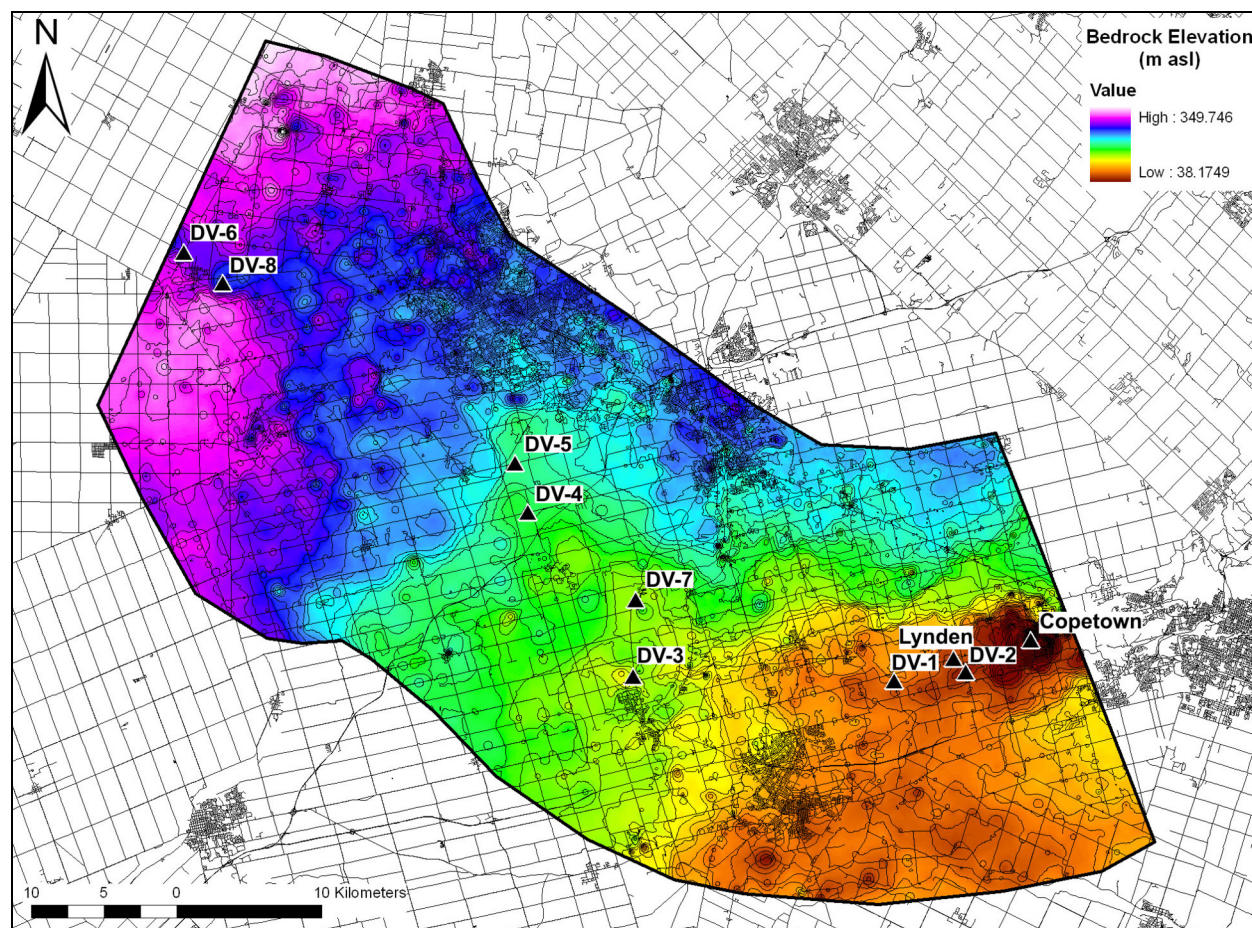


Figure 23.2. Prioritized areas identified for Phase 3 drilling and hydrogeological testing.

## Stratigraphy

A complex and highly varied stratigraphic record was recovered as part of the eight-hole overburden drilling program. Borings drilled within the lower reaches of the valley system (Figure 23.3: boreholes DV-1, DV-2, DV-3 and DV-7) display a relatively simple stratigraphic sequence consisting primarily of stratified deposits laid down during deglaciation of the area. Those boreholes drilled within the middle and upper reaches of the valley (see Figure 23.3: DV-4, DV-5, DV-6 and DV-8) contain much longer records including deposits that predate the last main advance of glacial ice into southern Ontario greater than 20 000 years ago. The aquifers recovered at depth within the confines of the valley thalwegs have disparate ages and are probably not connected hydraulically in the subsurface.

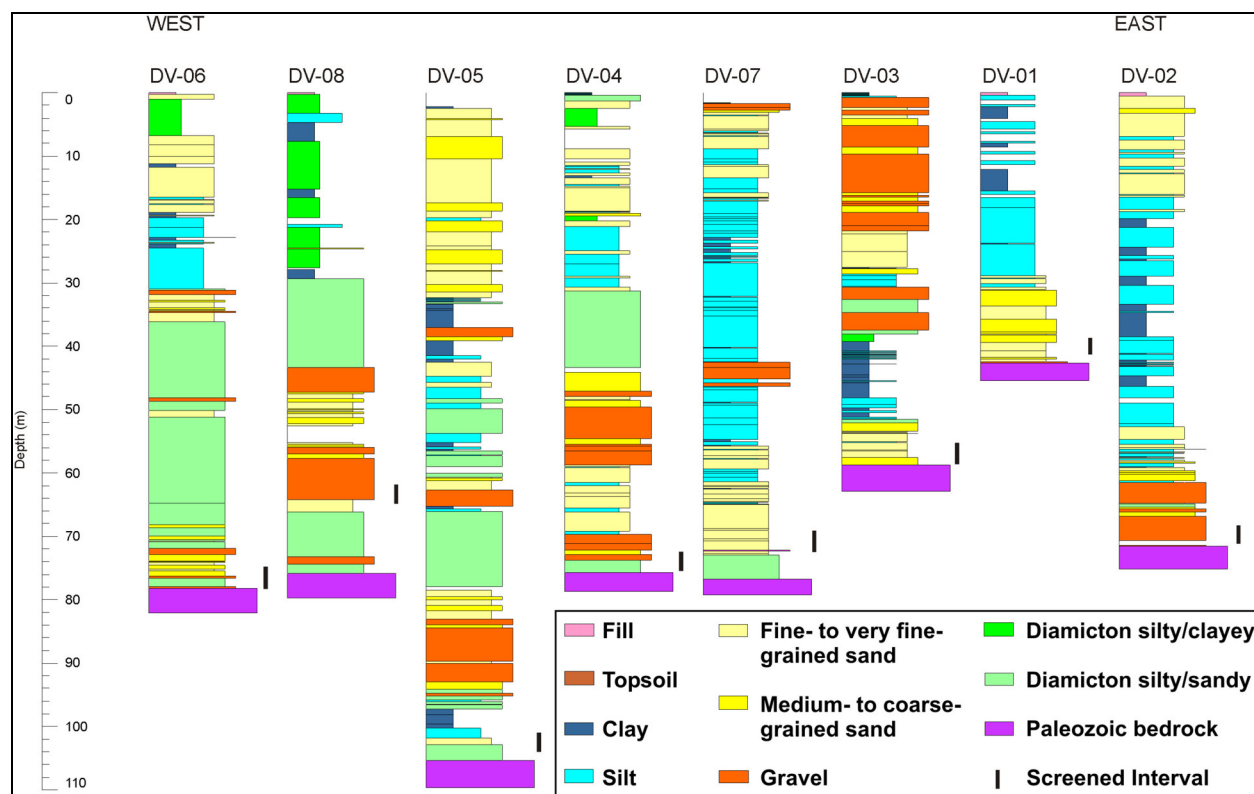
Boreholes drilled along the lower reaches of the Dundas buried valley range between 42 and 76 m in depth (Figure 23.4). A deeply buried aquifer was intersected in all of the boreholes. Those drilled east of the Paris and Galt moraines (DV-1 and DV-2) consist almost exclusively of well-laminated, glaciolacustrine silts and clays with lesser very fine-textured sands. Up to 12 m of medium- to coarse-grained sands and gravels underlie these deposits and rest directly on bedrock. West of the Paris and Galt moraines, the stratigraphic record becomes slightly more complex. At DV-3, just north of the Town of Paris, Grand River outwash deposits account for nearly half of the stratigraphic sequence. It is unclear how much erosion has taken place at this location, but it is likely that the underlying deep water glaciolacustrine deposits and interbedded diamictons represent Port Stanley drift laid down during slight oscillations of the ice margin as



**Figure 23.3.** Bedrock topography of the study area highlighting the location of the 8 continuously cored boreholes. Boreholes drilled at Lynden and Copetown as part of a joint project with the City of Hamilton are also shown (see Bajc et al., this volume).

the area was deglaciated. Approximately 7 m of very fine-textured sands underlie these deposits and rest directly on bedrock. The stratigraphic sequence recovered at DV-7 is similar to that recovered in DV-1 and DV-2. This borehole contained a thick sequence of glaciolacustrine silts and clays overlying a lower package of very fine-textured sands. This sand unit was isolated from the underlying bedrock by a 4 m thick diamicton likely correlative to Catfish Creek Till. The origin of an unusual gravel unit sandwiched between deep water deposits higher up in the sequence (~43 m) is not known. It is possible that a significant unconformity occurs at this level.

Boreholes drilled in the middle reaches of the valley system (DV-4 and DV-5) contain a similar record to that found within the Waterloo Moraine to the north (Bajc and Shiota 2007). Boreholes DV-4 and DV-5 had depths to bedrock of 76 and 106 m, respectively. An upper sequence of stratified sands with subordinate silt occurs in both holes and likely correlates with the Mannheim aquifer as defined by the Region of Waterloo. At DV-4, the sands are overlain by a thin capping of silty Port Stanley Till. As is commonly found in areas to the north, the Waterloo Moraine stratified sands are underlain by deep water silts and clays. These deposits are, in turn, underlain by Catfish Creek drift, which consists of a stony, silty to sandy till and associated stratified deposits. The main confining till unit in both DV-4 and DV-5 is approximately 12 m thick. A significant aquifer consisting of well-bedded medium- to coarse-grained sand and gravel with lesser very fine-textured sand was encountered in both boreholes. At DV-4, a silty, very fine-grained sand unit containing fine organic detritus is sandwiched between a pair of highly permeable gravel units (~59 to 70 m). Diamicton and fine-grained glaciolacustrine sediments underlie the aquifers in both DV-4 and DV-5. A weathering horizon with fossil mollusc remains was encountered at the top of this unit in DV-5 (96.6 m). This older stratigraphic unit may be correlated to Canning drift, a package of diamictons and stratified deposits belonging to either the Illinoian Episode or the Ontario Subepisode.



**Figure 23.4.** Graphic borehole logs for the 8 boreholes drilled within the Dundas buried valley study area. Note that all boreholes are hung from the same datum. The difference in collar elevation between DV-6 and DV-2 is approximately 150 m.

**Table 23.1.** Hydraulic testing summary (*adapted from Macdonald and Greer 2009*).

Location	Screen Interval	Flow Rate (l/s)	Test Duration (hours)	Transmissivity (m <sup>2</sup> /s)	Hydraulic Conductivity (m/s)	Storativity
DV-4	72.69 – 75.4	0.13	3	$9.00 \times 10^{-5}$	$3.00 \times 10^{-6}$	$5.36 \times 10^{-4}$
DV-5	100.85 – 103.9	0.09	4	$8.50 \times 10^{-6}$	$8.50 \times 10^{-6}$	$1.06 \times 10^{-3}$
DV-6	75.13 – 78.18	0.13	3	$1.60 \times 10^{-4}$	$1.10 \times 10^{-5}$	$8.26 \times 10^{-3}$

Two boreholes drilled in the upper reaches of the Dundas valley study area near the community of Wellesley both encountered a fairly similar stratigraphic sequence. Depth to bedrock in boreholes DV-6 and DV-8 were both in the range of 77 m. In borehole DV-6, an upper 6 m thick unit of fine-grained Huron lobe diamicton caps an 11 m thick coarsening-upward sequence of silt and clay grading to very fine-textured sand. The equivalent unit in DV-8 consists almost exclusively of interbedded silty to clayey diamicton and glaciolacustrine deposits. This unit rests on a 14 to 20 m thick unit of Catfish Creek Till and associated stratified sands. The stratified sands in borehole DV-6 occur at the top of the Catfish Creek Till sequence and contained fine-textured detrital organic material. Dense, overconsolidated Catfish Creek Till in these boreholes acts as an excellent confining unit. In borehole DV-8, up to 22 m of well-bedded sand and gravel underlies Catfish Creek Till. Many of the local domestic wells tap into this unit for their water supply. The equivalent unit in borehole DV-6 consists of less than 1 m of very fine-textured sand. This unit is underlain by approximately 27 m of silty to sandy diamicton, the lower 10 m of which consists of interbedded diamicton and sand and gravel. The upper surface of this diamicton displays strong oxidation and contains some black staining reminiscent of soil formation. A similar, 10 m thick unit of silty to sandy till at the base of borehole DV-8 was also encountered. This unit likely belongs to the Canning Till.

## Aquifer Testing

To hydraulically and geochemically characterize the aquifers, each of the monitoring wells established as part of the program was sampled and subjected to a short-term pumping test. These tasks were completed in March 2009 by WESA Inc., a geoscience consulting firm.

At each location, a datalogger was installed in the monitoring well at least 1 week prior to the start of the hydraulic testing to establish background water levels. In all cases, the electronic measurements were confirmed with manual water level measurements. During the background water level monitoring phase, no fluctuations in excess of 0.3 m were noted and, on average, water levels fluctuated 0.1 m (Macdonald and Greer 2009).

The duration of pumping tests ranged between 1 and 4 hours. Within the limitations imposed by the capacity of the pump that could physically fit into the monitoring well and the properties of the aquifer, the targeted drawdown in the pumping well was maximized. The average pumping rates used in the testing program ranged between 3.6 and 7.8 litres per minute (Macdonald and Greer 2009). Pumping rates were monitored during the testing and carefully controlled. Water level measurements continued until recovery was effectively complete. Throughout the testing period, the discharge was monitored for pH, conductivity, temperature, dissolved oxygen and oxidation–reduction potential (ORP). Of the 8 wells tested, 3 of them responded to pumping in a way that provided the necessary information for estimating aquifer hydraulic properties. The 3 wells that responded sufficiently to pumping (DV-4, DV-5 and DV-6; Table 23.1) were not screened directly in the most prominent aquifer, but rather at the overburden–bedrock contact. The response of the water level to pumping was interpreted with Aquifer Test<sup>TM</sup> for Windows<sup>®</sup> version 4.2 software using the Theis and the Papadopoulos and Cooper solutions (Macdonald and Greer 2009).

At the end of each hydraulic test, groundwater samples were collected and analyzed for dissolved metals as well as a suite of general chemistry parameters. The general chemistry and metals analysis were performed by Maxxam Analytics Inc. of Mississauga, Ontario. Samples were also collected for isotope analysis including oxygen, deuterium and tritium. The isotopic analyses are currently being completed by the University of Waterloo Isotope Lab. In terms of quality assurance/quality control for the groundwater sampling program, 1 field duplicate sample was collected and analyzed for general chemistry parameters.

The groundwater sampling results showed that the poorest water quality, from a drinking water perspective, was found at DV-02 and DV-04, where levels of hardness, total dissolved solids (TDS) and iron exceeded the Ontario Drinking Water Quality (ODWQ) Standards (Ontario 2003). The ODWQ standards were also exceeded at DV-4 for sulphate and at DV-2 for sodium and chloride. The water quality observed at DV-4 is likely a reflection of the geochemistry of the underlying Salina Formation bedrock which is typically characterized by elevated hardness, iron, TDS and sulphate (Singer, Cheng and Scafe 2003). Water geochemistry at DV-2 is not as easily understood and is likely a composite signature of both the Lower Silurian bedrock and overlying gravels of the contact aquifer. With the exception of elevated hardness and iron, the sampling results for the other 6 wells (DV-1, DV-3 and DV-5 to DV-8) showed good water quality in comparison with DV-2 and DV-4 and would likely be suitable drinking water sources from a groundwater quality perspective.

## NEXT STEPS

A continuation of the drilling, groundwater sampling and hydrogeological testing outlined in Phase 3 of the study is planned for the fall of 2009. This work will include the installation of pumping wells in the vicinity of DV-4 and DV-5, with the well screens placed in the thick sand and gravel aquifer units identified in the stratigraphic logs. Multi-level observation wells will also be installed within 100 m of both pumping wells as well as in the vicinity of DV-3. Pumping tests will be completed to evaluate the connectivity of valley deposits and to better estimate the hydraulic properties of the targeted aquifers. Hydraulic testing will be followed by groundwater sampling. The hydrostratigraphic and geochemical information derived from this work will be incorporated into the existing conceptual model. The field portion of the project will be finalized in the fall of 2009 and a final report completed in 2010.

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# 24. Project Unit 06-026. An Evaluation of Deeply Buried Aquifers Along the Dundas Buried Valley at Lynden and Copetown, Southern Ontario

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## INTRODUCTION

The Ontario Geological Survey (OGS) and the City of Hamilton have collaborated to undertake a study of deep confined aquifer systems within the Dundas buried valley sediments in the vicinity of the communities of Lynden and Copetown, southern Ontario (Figure 24.1). The City of Hamilton is interested in investigating these potential aquifer units as a municipal water supply. This study also adds to the ongoing three-dimensional (3D) mapping by the OGS concerning Dundas buried valley sediments and adjacent bedrock aquifers.

## FIELD WORK ACTIVITY

Field work associated with this study included the coring of 2 boreholes: one in Lynden and one in Copetown. The Lynden hole was cored and completed as a multi-level groundwater monitoring well with one screened section in bedrock within the Goat Island Formation and one in the sand and gravel unit associated with Wentworth Drift. The Copetown hole was completed as a groundwater monitoring well screened in the deep gravel unit associated with the Wentworth Drift. The groundwater monitoring wells at both locations were sampled for general chemistry parameters, metals and volatile organic compounds (VOCs). Hydraulic testing was completed at both locations to estimate hydraulic conductivity.

## GEOLOGY

The borehole drilled at Lynden is located on Governors Road just east of the community. It is likely collared on the northern flank of the Dundas buried bedrock valley with the main valley axis located just over a kilometre to the south (*see* Figure 24.1). Bedrock consisting of bituminous dolostone of the Eramosa Formation was encountered at a depth of 53.3 m. Within the Quaternary section of the borehole, 3 distinct sediment packages have been identified: an upper unit (Halton Drift: HD), approximately 12 m thick, consisting of well-laminated silts and very fine-textured sands, a middle unit (Lake Whittlesey–Warren Clays: LWWC), approximately 29 m thick, consisting of 3 fining-upward cycles of silty very fine-textured sand grading to well-laminated clay, and a lower unit (Wentworth Drift: WD), 7.9 m thick, consisting of silty and sandy diamicton capping a sequence of medium- to coarse-grained sand and gravel (Figure 24.2). This lower diamicton and associated stratified drift is interpreted to be associated with the retreating ice sheet responsible for the deposition of the Wentworth Till. The overlying glaciolacustrine

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*Summary of Field Work and Other Activities 2009,*  
*Ontario Geological Survey, Open File Report 6240, p.24-1 to 24-6.*

deposits are deep water basinal sediments interpreted to be laid down in glacial lakes Whittlesey and Warren, precursors of Lake Erie, approximately 13 000 years BP. The slight coarsening sequence observed in the upper laminated silts and very fine-textured sands may be associated with a late-stage readvance of the Ontario ice lobe, which resulted in the deposition of Halton Till.

The bedrock units cored to test the hydrogeological character in the Lynden borehole include in ascending order, using terminology of Brunton (2008, this volume): the Cabot Head, Fossil Hill (= Merritton Fm), Rockway, Irondequoit, Rochester, Gasport, Goat Island (Ancaster Member) and Eramosa (Vinemount and Reformatory Quarry members) formations (Figure 24.3). General descriptions of these rock units can be found in Brunton (this volume). Typical lithofacies relationships are observed in this core. The contact between the Cabot Head and Merritton formations is sharp and represents a long hiatus of erosion and/or non-deposition or extremely slow sedimentation as noted by the large phosphate pebbles within and at the contact between the basal Merritton Formation dolostones and underlying Cabot Head shales. The Rockway Formation is approximately 2 m thick and displays the characteristic welded contact with the overlying Irondequoit Formation. This latter formation, which is less than 1 m thick, is a bioturbated crinoidal encrinite that constitutes a good regional marker bed (*see* Brunton, this volume). The Gasport Formation in this core hole, which forms the main bedrock aquifer unit north of Hamilton to Cambridge–Hespeler and Guelph regions and extending up to Tobermory on the Bruce Peninsula, is only 3.5 m thick and is a poor aquifer unit. The overlying Goat Island Formation was screened because it is relatively thick and occurs between 2 regional aquitard units: the underlying Rochester Formation and the

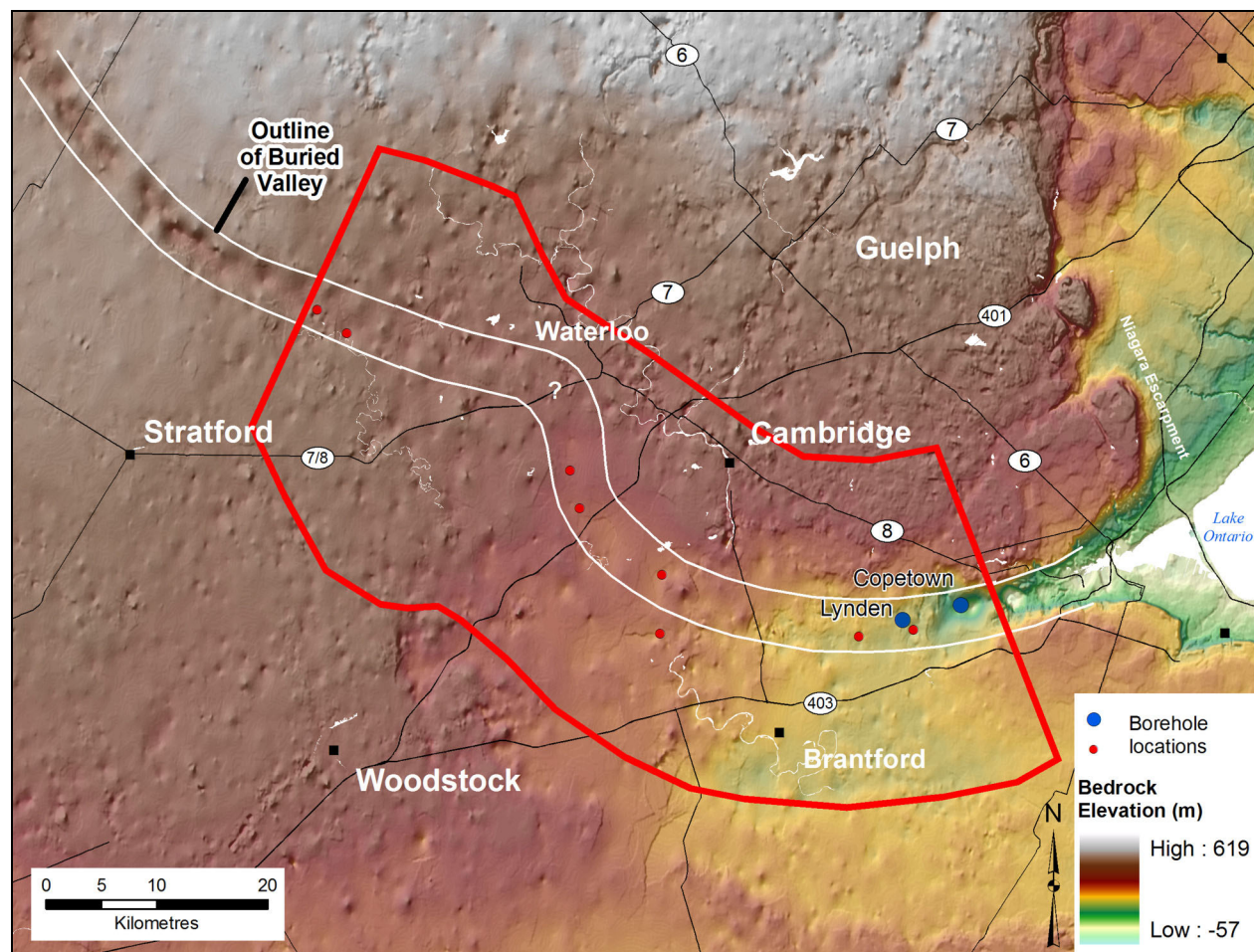


Figure 24.1. Location of Lynden and Copetown holes within Dundas buried valley study area.

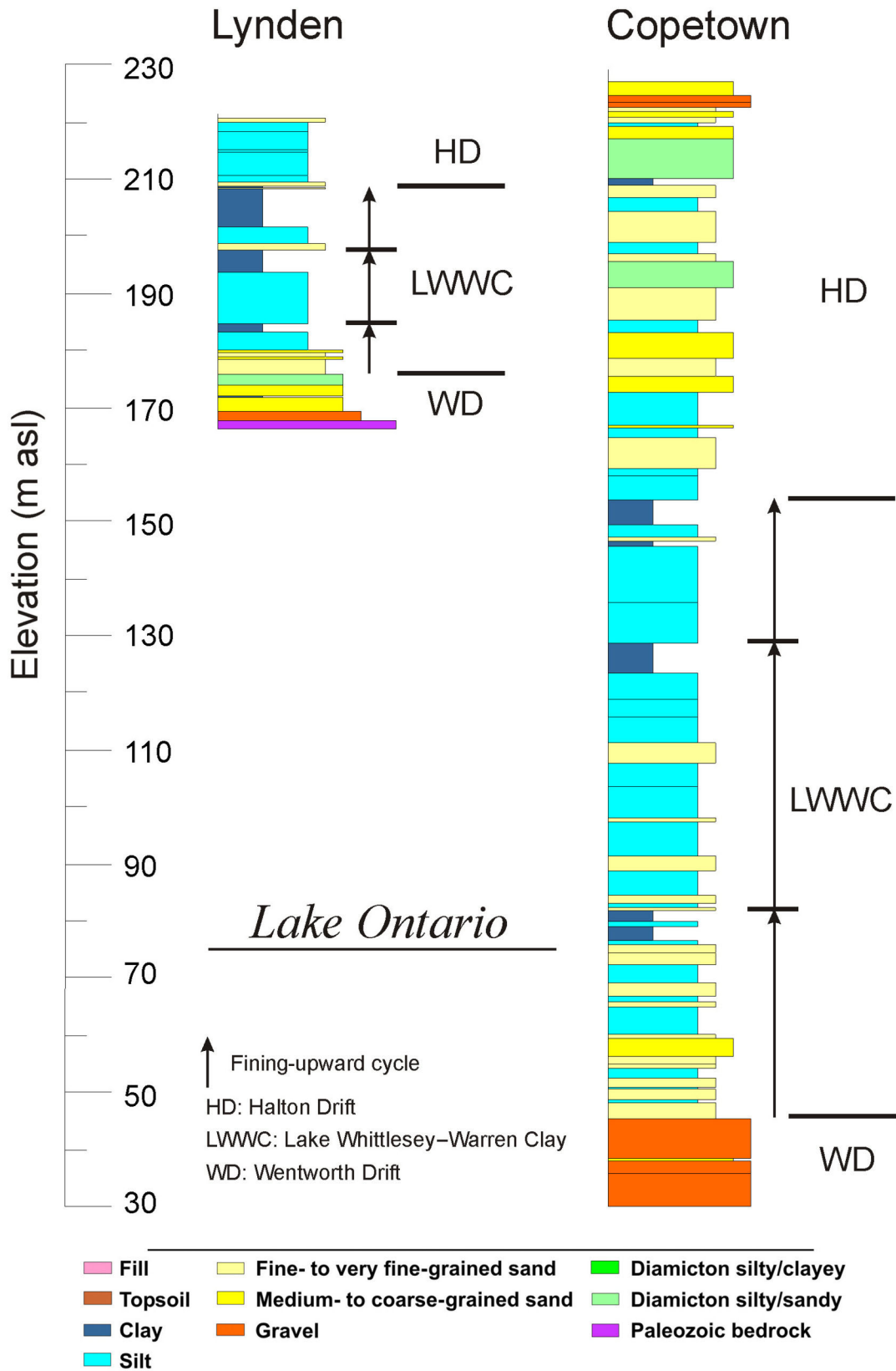


Figure 24.2. Graphic logs of borings drilled at Lynden and Copetown, southern Ontario.

overlying Vinemount member of the Eramosa Formation. There is a thin green shale unit at the top of the Rochester Formation that is most likely equivalent to the Glenmark Shale of New York State. This thin rock unit can be traced through the Cambridge to Mannheim areas of Kitchener–Waterloo region. The poor water quality of the Goat Island Formation dolostones and character and inferred low capacity of the Gasport Formation encrinites in this region of the Niagara Escarpment does not favour this hole as a water supply well.

The Copetown hole was drilled at the corner of Governors Road and Regional Highway 52, approximately 5.5 km east of the Lynden hole. The boring extended to a depth of 198.1 m and did not penetrate bedrock. The base of the hole is located at an elevation of about 30 m asl, 44 m below the level of Lake Ontario. Geotechnical borings on the Burlington bar to the east suggest valley incision to depths well below sea level (Karrow 1987). The sediment record observed in the Copetown hole is similar to that recovered at Lynden although expanded over a much greater thickness. An upper package (Halton Drift),

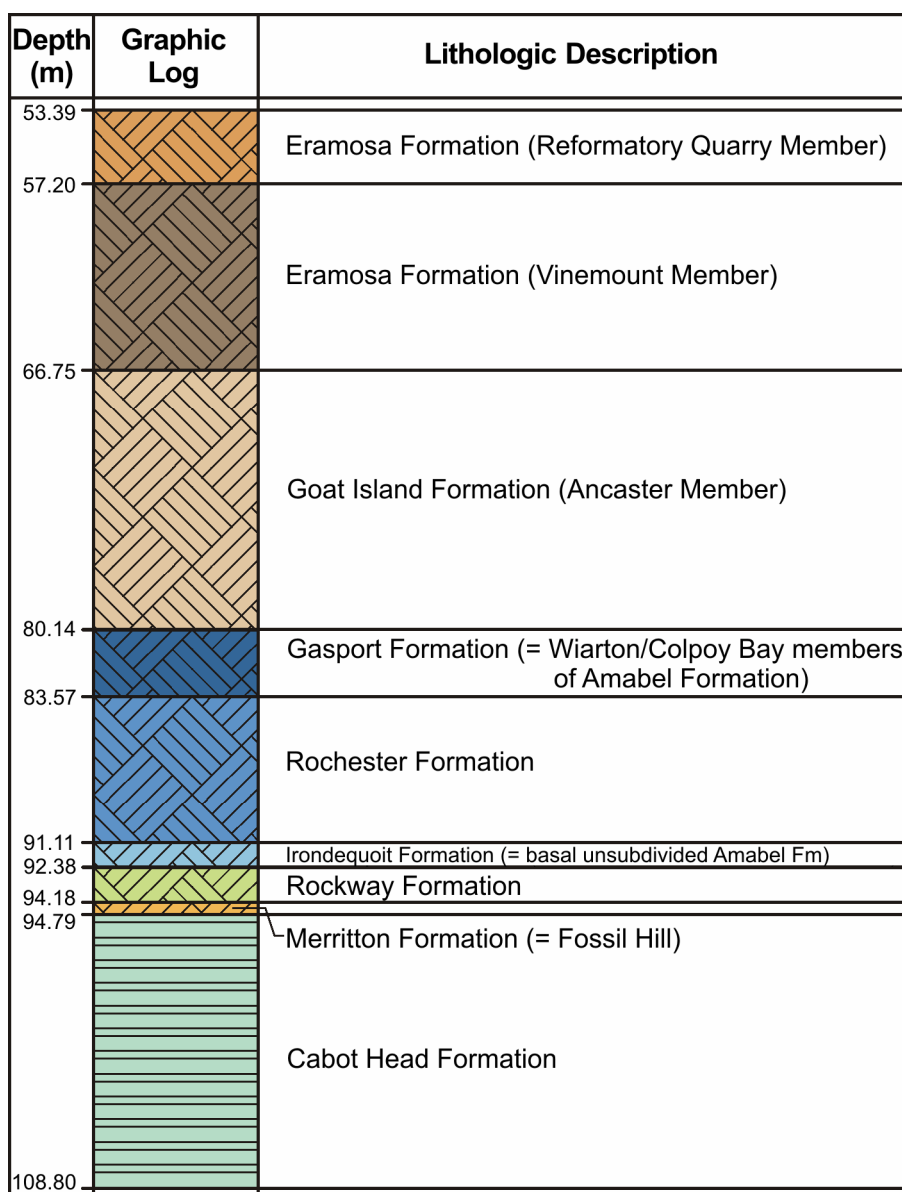


Figure 24.3. Graphic log of cored bedrock hole at Lynden, southern Ontario.

approximately 75 m thick, consists of interbedded silts, fine- to very fine-textured sands and silty and sandy diamicton presumably deposited along a Halton ice margin during the Port Huron Phase. A series of distinct ice-marginal ridges, referred to as the Waterdown Moraines, have been mapped by Karrow (1987) along the north side of the Dundas valley re-entrant. The trend of these ridges is in line with the position of the Copetown boring. A middle package of glaciolacustrine deposits (Lake Whittlesey–Warren Clays), approximately 108 m thick, displays 3 fining-upward cycles consisting of silty very fine-textured sands and silts grading up to well-laminated clays and silty clays. Significant deformation structures suggestive of rapid sedimentation, dewatering, slumping and mass flow processes were observed within this unit. This unit is abruptly underlain by 15.2 m of well-bedded pebble to cobble gravel, gravelly sand and medium- to coarse-textured sand (Wentworth Drift) that is reported to have yielded in excess of 800 L per minute of water (Procore Drilling Ltd., personal communication, 2009). This unit is correlated with the lowermost unit in the Lynden hole the base of which is on bedrock.

## HYDROGEOLOGY

To evaluate water quality, groundwater sampling was conducted from the monitoring wells at both the Lynden and Copetown locations. Groundwater samples were analyzed for general chemistry parameters, metals and VOCs. Prior to installation of the monitoring wells at the Lynden location, 2 additional rock sections were isolated and sampled for metals and general chemistry parameters. These 2 sections included the Rochester and Eramosa formations. In general, the chemistry for the Rochester and Eramosa formations was very similar with slightly elevated total dissolved solids (TDS), hardness and sodium (Veale and Freymond 2009). The similarity in chemistry between these 2 formations is unexpected and may represent a blending of the waters from the isolated section of interest and the water in the open hole. The groundwater chemistry of the Goat Island Formation showed significantly elevated TDS, hardness, sodium and chloride with slightly elevated manganese (Veale and Freymond 2009). The overburden well showed good water quality from a drinking water supply perspective with low metals levels, low TDS and only slightly elevated sodium. Volatile organic compounds were not detected in any of groundwater samples taken from the Lynden hole (Veale and Freymond 2009). Detailed rock litho-geochemistry (whole rock and trace elements) and chemostratigraphy of the entire succession is being carried out to help elucidate the water geochemistry results (*see* Brunton, this volume). To evaluate water quantity, hydraulic testing was completed at the Lynden location. This testing included a short-term pumping test in the open bedrock hole, prior to monitoring well installation, and a slug test in the overburden monitoring well (Wentworth Drift). The water level recovery data from the short-term pumping test in the open bedrock hole were analyzed using the Bouwer–Rice solution for a confined aquifer. The analysis yielded a hydraulic conductivity estimate of about  $2 \times 10^{-7}$  m/s for bedrock. The slug test data for the overburden monitoring well (Wentworth Drift) were also analyzed using the Bouwer–Rice solution for a confined aquifer and yielded a hydraulic conductivity estimate of  $1 \times 10^{-6}$  m/s, which is reasonable for a silty sand aquifer (Veale and Freymond 2009). Given the poor water chemistry and relatively low hydraulic conductivity estimate, further water supply investigation in bedrock in the Lynden area is not recommended. Hydraulic testing in bedrock at the Lynden location further confirmed that the Gasport Formation, which is the main regional bedrock aquifer system north of Hamilton and extending to the Bruce Peninsula and Manitoulin Island regions, is thin and unproductive in the area. Although the overburden aquifer showed promising water chemistry, the limited storage capacity does not make the Lynden locality suitable for further municipal water supply investigation.

At the Copetown location, the groundwater chemistry results showed poor water quality from a drinking water supply perspective. Significantly elevated TDS, hardness, sodium and chloride were detected. Elevated metals concentrations were also detected, including iron and manganese. Volatile organic compounds were not detected in the samples taken from the Copetown hole (Veale and Freymond 2009). Hydraulic testing results for the Copetown well are pending.

## **SUMMARY**

Based upon the poor water chemistry results (Copetown hole, Lynden bedrock hole) and limited water production (Lynden overburden and bedrock holes), further investigation of these locations as potential potable groundwater sources is not recommended.

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# 25. Project Unit 08-004. Update of Revisions to the Early Silurian Stratigraphy of the Niagara Escarpment: Integration of Sequence Stratigraphy, Sedimentology and Hydrogeology to Delineate Hydrogeologic Units

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## INTRODUCTION

Results presented are part of a four-year study (2008 to 2011) to map the bedrock aquifers, karst, and Early Silurian sequence stratigraphy of the Niagara Escarpment region of southern Ontario. More than 80 boreholes and numerous key outcrops have been examined in detail, spanning upper Cabot Head Formation to base of Salina Group. The time duration spans the late Llandovery through Wenlock with many discrete time breaks represented within a predictable sequence stratigraphic framework. This study enables better correlation of rock units between the northwestern subbasin of the Appalachian Basin and erosional-edge of the eastern Michigan Basin, and the development of a testable sequence stratigraphic and hydrostratigraphic framework along the Niagara Escarpment region of Ontario (Figure 25.1).

Key stratigraphic findings in the 2009 field season include

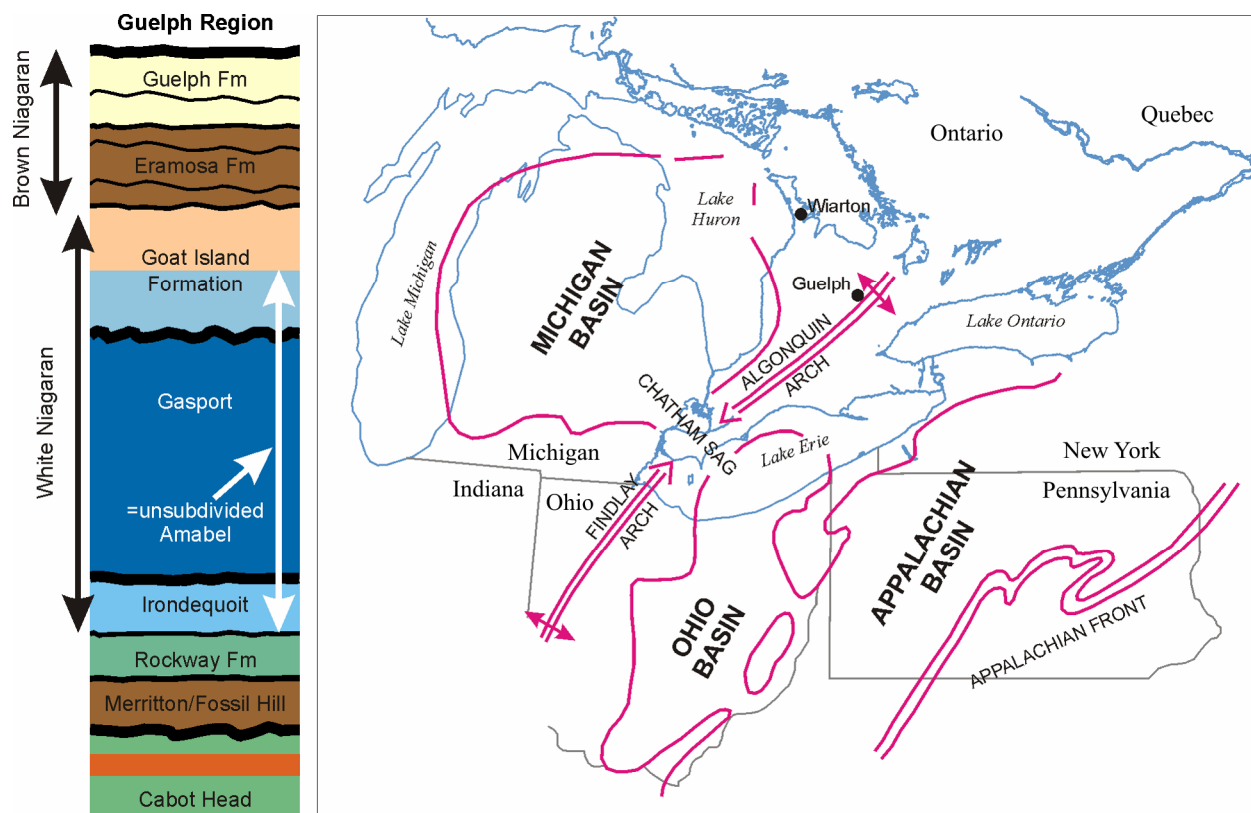
1. refinements concerning the significance of tectonically induced erosion below the upper Fossil Hill Formation (= Merritton Formation) (systematic removal of middle and lower Fossil Hill, underlying St. Edmund, Wingfield, Dyer Bay and uppermost Cabot Head formational rock units from Bruce Peninsula to Niagara Falls; *see Brintnell et al., this volume*);
2. the upper Fossil Hill (= Merritton Formation of Brett et al. 1995) Formation dolostone extends across the Algonquin Arch and is evident in core from Niagara Falls to northern Bruce Peninsula and Kincardine through Sarnia areas;
3. the Rockway Formation is a persistent shaly dolostone across the Algonquin Arch into the Bruce Peninsula region (Fossil Hill (upper unit = Merritton) and Rockway formations are frequently, but erroneously, referred to as the Reynales Formation in most areas of southern Ontario);
4. recognition of the regional extent of the Irondequoit Formation in Ontario (present in every core examined), which displays an erosional and welded contact (disconformable) on the Rockway Formation (this rock unit has been included with basal Amabel Formation crinoidal grainstones and not recognized as a discrete formation);
5. basal Lions Head Member of Amabel Formation appears to be a carbonate-facies equivalent of Rochester Formation (equivalent to upper Burleigh Hill or Stoney Creek members; *see Brett 1983; Brett et al. 1995*);
6. the Gasport Formation largely represents what has been called the Amabel Formation (comprising both the Warton and Colpoy Bay members; *see Bolton 1957; Liberty and Bolton 1971*), and is either disconformably overlain by the Goat Island Formation (Niagara Falls member and/or Ancaster member) or the Eramosa Formation (e.g., basal Vinemount member or

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- Reformatory Quarry member) or the Guelph Formation, thereby highlighting the significance of the erosion above the surface of the Gasport Formation;
7. the Eramosa is a regionally persistent and faunally and/or lithologically distinctive rock unit (possessing a distinctive seismite bed). The regional scope of this study has demonstrated that, because of this region-wide identification, the status of the Eramosa lithofacies as a formation should be acknowledged more generally. As done previously (*see* Brunton 2008), this paper will refer to those lithofacies assigned to the Eramosa interval as the “Eramosa Formation”. The author will formally propose the redefinition of formation rank for Eramosa lithofacies in a future publication (refereed journal article).
  8. revisions to the contact between the Eramosa and Guelph rock units and recognition of 3 previously unrecognized members of the Eramosa Formation (base to top: Vinemount member, Reformatory Quarry member and Stone Road member; *see* Brunton 2008);
  9. recognition of 2 informal rock units in the Guelph Formation (basal reef mound-bearing Wellington member and overlying megalodontid bivalve-gastropod-dominated Hanlon member).



**Figure 25.1.** Silurian paleogeography relative to the present-day erosional boundaries of key foreland (Appalachian) versus intracratonic (Michigan) basins of eastern North America. The red lines depict present-day erosional boundaries of the Michigan, Appalachian and Ohio basins in relation to the arches (areas where forebulge migration and development were influencing sedimentation between the basins on broad shallow shelf areas) (*modified from* Haynes 2000). The stratigraphic succession of interest for this multi-year bedrock mapping project is upper Cabot Head through Guelph formations. These strata represent mostly dolostones with minor noncalcareous and calcareous shales. The mounds depicted in the stratigraphic column represent phases of composite reef mound development within the transgressive systems tracts (TSTs) of the succession. Proposed stratigraphic revisions shown include the Gasport Formation (comprising the Warton and Colpo Bay members of the Amabel Formation). The blue and salmon colours for the Goat Island Formation represent the Niagara Falls member and the Ancaster member, respectively. The lines shown within the Eramosa and Guelph formations depict newly recognized members within type sections (*see text*). Michigan Basin subsurface terms for this stratigraphic interval are highlighted with arrows on left side of the stratigraphic section. Rock units that make up the Amabel Formation are also shown (white vertical line with arrows) and highlight the need to abandon this rock term in southern Ontario.

A regional drilling program is currently underway to better constrain whether some of the members outlined for the Eramosa Formation may be of formational rank (e.g., Stone Road member). The recognition of very significant erosional phases above the Gasport and Guelph formations, 2 surfaces which strongly influence the hydrostratigraphic character of the Niagara Escarpment cuesta, is being followed up with the drilling program of more than 25 cored holes being collected this fall along the Niagara Escarpment subcrop–outcrop belt. This work is a collaborative effort between the Ontario Geological Survey, City of Guelph, Regional Municipality of Waterloo, Halton Region, City of Hamilton, University of Guelph, Parks Canada and Ministry of Natural Resources.

This project is the first attempt by the Ontario Geological Survey (OGS) to systematically map and delineate discrete bedrock aquifers and aquitards within Silurian carbonate strata along the Niagara Escarpment region of southern Ontario (Niagara Falls to Tobermory and Manitoulin Island). The foundation of such studies is the development of a robust and testable sequence stratigraphic and structural framework that integrates vertical and lateral changes in the physical character of the sedimentary rocks. Detailed litho-geochemical analyses of the stratigraphic succession (whole rock and trace element geochemistry on metre scale) can then be compared to the hydrochemical character of the water-bearing rock units in order to define discrete hydrogeologic units (HGUs). Such an approach requires acquisition of detailed head profiles and hydrochemistry relative to the sequence stratigraphic and litho-geochemical framework.

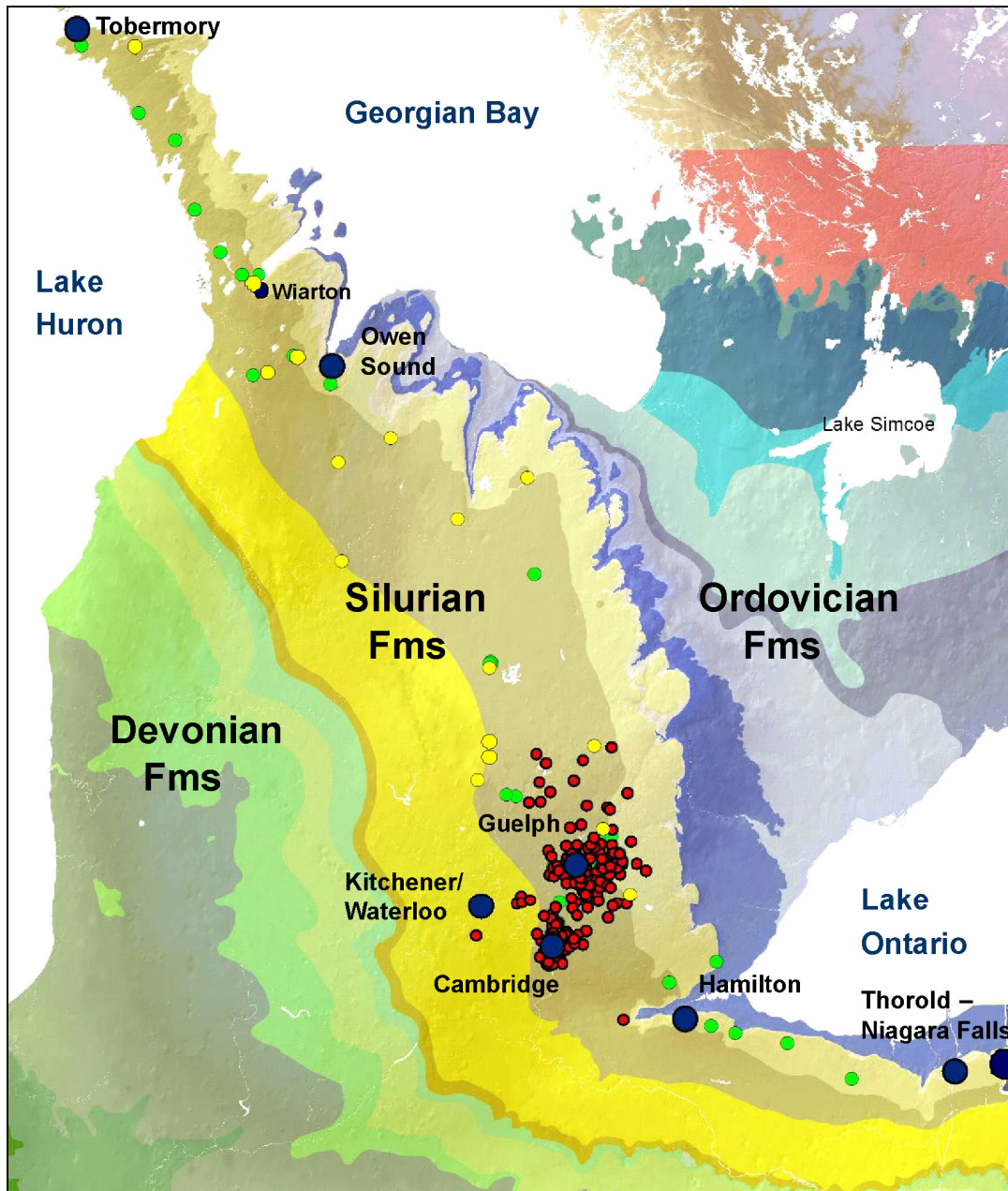
Detailed core logging, in combination with hydrogeological and litho-geochemical measurements, allows regional-scale aquitards and aquifers to be delineated. Such data can then be placed into a regional groundwater flow model that takes into account the major recharge and discharge areas. Compilation of these data provides the foundation to assess the sustainability of these vital resources as southern Ontario's population continues to grow and global pressures for water sharing increase. It is a little known fact that the majority of families in southern Ontario on private water wells and municipal water supplies rely on karst-influenced carbonate bedrock aquifers (Brunton and Dodge 2008; Brunton 2008). Provincial estimates of current usage and bedrock aquifer capacities are poorly constrained because no systematic studies have been carried out to date.

The key goals of the 2009 field season have been to integrate core and outcrop stratigraphic and sedimentologic measurements to establish a testable sequence stratigraphic framework for Early Silurian sedimentary carbonate strata in the vicinity of Hamilton–Halton through Guelph–Cambridge and eastern Kitchener–Waterloo and northward along the spine of the Niagara Escarpment to Tobermory and westward into the Michigan Basin region to Kincardine and Sarnia. These strata occur between the upper Cabot Head Formation shales (regional aquitard of Niagara Escarpment) and overlying Salina Group algal laminites and gypsiferous sabkha cycles. This interval includes strata that span the upper Medina, Clinton and Lockport groups of western New York and extending into southwestern Ontario from Niagara Falls to Hamilton (Brett, Goodman and LoDuca 1990; Brett et al. 1995). This project incorporates and builds upon the major revisions to Early Silurian strata nomenclature and lithologic descriptions outlined in Brett et al. (1995).

The average depth of the holes drilled as part of this study is 120 m. In the majority of the cored holes, downhole geophysics in the form of gamma, conductivity and optical televiwer logs, camera logs and standard hydrogeologic investigations (pumping and packer testing) have been carried out to provide a more comprehensive picture of the groundwater character in these Silurian strata (*see* Brunton 2008). The current drilling program (September–October 2009) of at least 16, 100 to 140 m deep HQ-diameter drill holes builds upon the more than 100 holes that have been used to create the three-dimensional geologic framework for Tier III groundwater modelling being undertaken by the City of Guelph and Regional Municipality of Waterloo (funded by the Ministry of Environment and Ministry of Natural Resources). Key additional drill core and outcrop sections were measured from Niagara Falls to Tobermory (Figure 25.2) and Manitoulin Island to provide a regional context to the newly proposed sequence stratigraphic framework.

## BACKGROUND AND SCOPE OF STUDY

This regional-scale groundwater mapping initiative builds upon previous studies concerning the industrial mineral potential of the Guelph and Eramosa formations (*see* Brunton and Dekeyser 2004; Brunton, Dekeyser and Coniglio 2005), as well as karst and groundwater in southern Ontario (Brunton, Dodge and Shirota 2005, 2006; Brunton et al. 2007; Brunton and Dodge 2008; Brunton 2008). In order to map out regional hydrogeologic units (HGUs) within Paleozoic sedimentary rocks of southern Ontario,



**Figure 25.2.** Paleozoic bedrock geology map of southern Ontario with locations of key drill holes and outcrop locations for 2008 and 2009 field seasons. The Early Silurian stratigraphic interval of interest spans the top of Cabot Head Formation through Guelph Formation (tan and beige bands that make up Niagara Escarpment region of southern Ontario). Red dots represent key borehole locations (2004–2008 core holes); green dots represent key outcrops and core holes drilled by OGS (1982–1990); and yellow dots represent 2009 core holes. Blue dots represent some of key cities and towns within study area of Niagara Escarpment region.

a detailed understanding of the sequence stratigraphy and lithofacies changes from the northwestern Appalachian to southeastern Michigan basins is required. Other key factors include the delineation of recharge and discharge areas, roles of various strata (sequences and smaller scale rock units) as aquifers and aquitards, and integration of hydrochemistry and lithogeochemistry. The integration of hydrochemistry and lithogeochemistry requires collaboration and implementation of innovative water-well sampling techniques (*see* Brunton 2008).

## PROPOSED REVISIONS TO THE SILURIAN STRATIGRAPHY OF THE NIAGARA ESCARPMENT

Strata described below, and which form part of this multi-year study, occur between the basal Cabot Head Formation shales (regional aquitard of Niagara Escarpment) and overlying Salina Group algal laminites and gypsiferous sabkha cycles (Figures 25.3 and 25.4). These strata sit above the significant unconformity associated with the top of the Cabot Head Formation shales and associated siliciclastic units referred to as the Thorold Sandstone, Cambria Shale, Kodak Sandstone, and other Clinton Group strata of west-central New York (i.e., Reynales and other formations; *see* Brett et al. 1995). These Early Silurian dolostones include strata that span the upper Medina, Clinton and Lockport groups of western New York that extend into southwestern Ontario from Niagara Falls to the Guelph area.

Age	Series / Stage	Bruce Peninsula (Bolton 1953, 1957)		Bruce Peninsula (Sanford 1969)		Bruce Peninsula (Liberty & Bolton 1971)		Niagara region (Brett et al. 1995)		Guelph area ("OGS 1992")		Bruce Peninsula / Guelph areas (This Study (revised OGS))							
		Group	Formation / Member	Group	Formation / Member	Group	Formation / Member	Group	Formation / Member	Group	Formation / Member	Group	Formation / Member						
Ludlow ?	Wenlock ?	Niagaran	Albemarle	Guelph	Amabel	Lockport Formation	Guelph Fm	Lockport	Guelph	Albemarle	Guelph	Lockport	Guelph						
				Eramosa			Eramosa Mbr		Eramosa		Eramosa Mbr								
Warton	Warton Mbr			Goat Island *			Goat Island *												
Colpo Bay	Colpo Bay Mbr			Gasport **			Gasport **												
Lions Head	Lions Head Mbr			Decew			Decew												
Llandovery	Alexandrian		Clinton	Fossil Hill	Fossil Hill	Cataract	Cabot Head Formation	Clinton	Clinton	Reynales	Cataract	Reynales	Clinton	Thorold & Grimsby & Cabot Head					
				St. Edmund	St. Edmund										Member 2	Member 2			
				Wingfield	Wingfield										Member 1	Member 1			
				Dyer Bay	Dyer Bay										St. Edmund Mbr	St. Edmund Mbr			
				Cabot Head	Cabot Head										Wingfield Mbr	Wingfield Mbr			
		Manitoulin	Manitoulin	Manitoulin	Manitoulin	Manitoulin	Manitoulin	Manitoulin	Manitoulin	Manitoulin	Manitoulin	Manitoulin	Manitoulin	Manitoulin	Manitoulin				
																Warton	Warton Mbr	Warton & Colpo Bay Mbr	Warton & Colpo Bay Mbr
																Colpo Bay	Colpo Bay Mbr	Lions Head Mbr	Lions Head Mbr
																Lions Head	Lions Head Mbr	Rochester ***	Rochester ***
																Fossil Hill	Fossil Hill	Irondequoit	Irondequoit
St. Edmund	St. Edmund	Rockway	Rockway																
Wingfield	Wingfield	Williamson	Williamson																
Dyer Bay	Dyer Bay	Merritton	Merritton																
Cabot Head	Cabot Head	Reynales	Reynales																
Manitoulin	Manitoulin	Neagha	Neagha																

**Figure 25.3.** Selected Early Silurian stratigraphic nomenclature for Niagara Escarpment region of southern Ontario (*see* descriptions in text; *see also* discussions in Brunton 2008; *see also* Figure 25.4). Abbreviations: Fm, Formation; Mbr, Member; "OGS 1992" refers to Johnson et al. (1992). Note, other stratigraphic units are mentioned in the text (*from* Brett 1983 and Brett et al. 1995): \*Goat Island Dolomite [Formation], from top to bottom: Vinemount, Ancaster and Niagara Falls members; \*\*Gasport Formation, from top to bottom: Pekin Member and Gothic Hill Member; \*\*\*Rochester Shale [Formation], from top to bottom: Stoney Creek, Burleigh Hill and Lewiston members.

This project incorporates and builds upon the major revisions to Early Silurian stratigraphic nomenclature and lithologic descriptions outlined in Brett et al. (1995). The nomenclature adopted below for the Early Silurian stratigraphy of southern Ontario differs from that outlined in the *Geology of Ontario* volume (Johnson et al. 1992) and recent updates of the Paleozoic stratigraphy of southern Ontario (Armstrong and Carter 2006, p.17; Armstrong and Dodge 2007). The significant differences between the overall stratigraphic nomenclature outlined by Brett et al. (1995) and that of this study include recognition

Preliminary Revisions to Silurian Stratigraphy			Hydrostratigraphy Karst Aquifers
Lithology	Formation	Member	Aquifers
	Guelph	Hanlon	← "Unconfined" Bedrock Aquifer Guelph HGU
		Wellington	
	Eramosa	Stone Road	Regional Aquitard
		Reformatory Quarry Vinemount	
	Goat Island	Ancaster	Lower transmissivity zone
		Niagara Falls (=unsubdivided Amabel Fm)	
	Gasport	Gothic Hill	← Main ← "Confined" Bedrock Aquifer ← Gasport HGU
		(Lions Head Mbr = Rochester Fm) (=previous unsubdivided Amabel Fm)	
	Irondequoit	(=unsubdivided Amabel Fm)	Lower transmissivity zone
	Rockway		← Minor confined aquifer
	Merritton	(=Fossil Hill Fm)	
	Cabot Head		Regional Aquitard

**Figure 25.4.** Proposed revised sequence stratigraphic framework for Guelph through Tobermory areas of Niagara Escarpment. The relative thickness of lines separating each formation in right column reflects the significance of the diastem (thicker line reflects greater time break). Key aquitards include the regional Cabot Head Formation shales, dolostones of the overlying Merritton and Rockway formations, and the Vinemount member and calcareous shales of the Eramosa Formation. In the Cambridge through Hamilton regions and extending eastward toward Niagara Falls, the Rochester Formation is situated between the Irondequoit and Gasport formations and behaves as an aquitard, in part. The Merritton Formation is equivalent to the upper part of the Fossil Hill Formation. There are sharp contacts between these formations. Re-examination of OGS core drilled on the Bruce Peninsula and newly acquired core reveal that, on the Michigan Basin side of the ephemeral forebulge that influenced sedimentation across the Algonquin Arch, a carbonate unit previously referred to as the basal Lions Head Member of the Amabel Formation is a carbonate equivalent to facies of the Rochester Formation shales to south and east. The Niagara Falls member of the Goat Island Formation is a relatively low transmissivity crinoidal grainstone unit. Previous hydrogeology studies in the Guelph–Cambridge through Acton areas have allocated the Irondequoit and Gasport formations and Niagara Falls member of the Goat Island Formation to the unsubdivided Amabel Formation. Key regional hydrogeologic units (HGUs) include the Gasport Formation cycles of reef mound and transgressive basal inter-reefal bleached shell coquinas and encrinites. A less significant bedrock aquifer system is evident locally in the lower Guelph Formation: within and at the Stone Road member and basal Wellington member contact, at the contact between the Wellington and Hanlon members, and at the top of bedrock. This key unconfined aquifer is known as the Guelph interface aquifer (ground waters flowing along bedrock surface and within basal unconsolidated Quaternary sediments; see Brunton 2008).

that 1) the Irondequoit Formation, which belongs to the Clinton Group and extends across the Algonquin Arch and throughout southern Ontario, has been erroneously lumped into the basal Amabel Formation; 2) the Lions Head member of the basal Amabel Formation is actually a carbonate equivalent of part of the Rochester Formation (and not equivalent to the Rockway Formation as outlined in Brett et al. (1995) and as stated in Brunton (2008)); 3) the Vinemount Shale Beds (or Vinemount beds; referred to herein as Vinemount member), which were placed in the upper Goat Island Formation by Brett et al. (1995), better correlate with lithofacies assigned to the Eramosa Formation throughout southern Ontario; and 4) the Eramosa Formation has 3 previously unrecognized units that could be all assigned member status. The Guelph Formation also comprises 2 mappable units that have been assigned member names (*see* Figure 25.4). Some key details are outlined below.

### **Fossil Hill Formation (= Merritton Formation, in part)**

The type section for the Fossil Hill Formation is located on Manitoulin Island in a roadcut at the intersection of Highway 6 and New England Road, approximately 10 km southwest of Manitowaning (Bolton 1953, 1957; Winder 1961). Williams (1919, 1937) referred to this rock unit as the Lockport. This unit can be separated into lower, middle and upper parts based on faunal components and lithofacies. There are, in fact, at least 4 significant erosional breaks or small-scale sequence boundary surfaces evident in the type section. The lower unit possesses a brachiopod-rich succession with large pentamerid brachiopods in condensed beds, suggesting low sedimentation rates. The lower one-third to middle part of the formation, as revealed in the type section on Highway 6, consists of poorly fossiliferous lime mudstone to wackestone and superficially resembles the underlying St. Edmund or Mindemoya Formation (termed the “false Mindemoya”). This “false Mindemoya” or St. Edmund Formation lithofacies is present in the northern cores on the Bruce Peninsula and thickens northward to the type section on Manitoulin Island. Hard grounds are present in this unit. The upper one-third of the Fossil Hill Formation shows a return to richly fossiliferous brachiopod beds of *Pentameroides* (not *Pentamerus*) and an abundant megafauna of tabulate corals and calcified sponges and related faunas. No bioherms have been described from this unit. The condensed nature and taphonomic character of the fauna in core indicates palimpsest conditions and a slow sedimentation rate. There are at least 4 significant disconformities in the Fossil Hill Formation at its type section on Manitoulin Island (*see also* Stott and von Bitter 1999).

The Fossil Hill Formation is very cherty and well indurated, which partly accounts for its regionally extensive nature. It is present from northern Michigan (where it is also known as the Manistique Formation) to Niagara Falls, where it is referred to as the Merritton Formation (Brett et al. 1995; Brunton 2008). Other good exposures of the Fossil Hill Formation are located on the Bruce Peninsula, on the shore of Isthmus Bay, just north of the village of Lion’s Head, and in a roadcut near Inglis Falls, just south of Owen Sound (Bolton 1957; Liberty and Bolton 1971; Armstrong, Goodman and Coniglio 2002; Armstrong and Carter 2006; Armstrong and Dodge 2007; *see also* Brintnell et al., this volume, Figure 26.1).

The Fossil Hill Formation in southern Ontario is everywhere disconformably overlain by the Rockway Formation (*see* discussion below) from the northern Bruce Peninsula to Niagara Falls. In general, the *Pentameroides*-dominated facies of the upper Fossil Hill Formation seems to be a regionally persistent rock unit. Of equal significance is the fact that the Irondequoit Formation is a persistent, thoroughly bioturbated crinoidal grainstone to packstone lithofacies that is present from Tobermory to Kincardine and in cores from the Chatham Sag area to Niagara Falls (Brunton et al. 2009; Brunton, Turner and Armstrong 2009).

The upper Fossil Hill (= Merritton) Formation rests disconformably above the Cabot Head Formation shale in cores from the Guelph area. This upper Fossil Hill Formation rock unit was originally identified as a member of the Reynales Formation (Kilgour 1963), which has produced some confusion in nomenclature. Strata referred to as the Merritton Formation (= upper Fossil Hill Formation) are generally less than a metre thick and appear to thin to the east, toward the present-day cuesta margin. This rock unit

is thicker in some cores in Guelph than at the type section in Thorold. It possesses the same pentamerid brachiopods and tabulates as the Fossil Hill Formation and is, therefore, correlated with that formation. It has been previously incorrectly assigned to the lower Reynales Formation of New York State, which is much older (Brett et al. 1995, p.31-34).

From the Luther Lake–Mount Forest area to Niagara Falls, this distinctive formation comprises up to 3 well-indurated beds of unequal thickness that are separated by dark, shaly partings (upper Fossil Hill Formation = Merritton Formation). The basal bed has a distinctive, bioturbated, pinkish-brown finely crystalline matrix. It possesses a black, phosphate pebble-bearing hardground unit in the lower beds. The middle bed possesses *Planolites*-type burrows, which locally contain glauconite, and the lower beds are rich in pyrite. The lower beds are wackestones, whereas the upper bed exhibits pentamerids (*Pentameroides subrectus*) and halysitid and favositid corals typical of the upper Fossil Hill Formation. The uppermost, brachiopod-rich beds are rarely evident in core from the Guelph region.

This formation acts as a regional aquitard that enables waters to remain above the Cabot Head Formation shales and reside in the overlying karstic Gasport Formation aquifer (Gasport hydrogeologic unit). If the Merritton Formation were not present in the Guelph–Cambridge region, formational waters would most likely flow along the upper Cabot Head shale aquitard and the City of Guelph region would not have one of the best karst-influenced bedrock aquifers in southern Ontario. This formation thickens northwestwardly to its type section on Manitoulin Island.

## Rockway Formation

The Rockway Formation was originally assigned to the lower member of the Irondequoit Formation (Kilgour 1963). It was subsequently elevated to formational status with the recognition that it had an unconformable contact with the overlying crinoidal dolostones in the Irondequoit Formation (*see* Brett et al. 1995). This formation possesses a distinctive, greenish-grey fine crystalline matrix separated by styloseam sets and thin shaly partings. It is an argillaceous dolomicrite to wackestone with no discernible macrofaunal elements. The Rockway Formation has a fairly consistent thickness of 1 to 2 m throughout the study area and, unlike the underlying Merritton Formation, is present in every core. It has a very distinctive and erosional contact with the overlying Irondequoit crinoidal grainstone unit, making it easy to delineate in the core. This contact is best described as “welded”, and its distinctive character in every core within the Guelph region proves the existence of a widespread disconformity, but not highly erosional contact, between the Rockway and Irondequoit formations. The Rockway Formation persists north of Hamilton, across the Algonquin Arch, and is present in every core examined from the Sarnia area through Kincardine to Tobermory and down the Niagara Escarpment cuesta region. The lack of significant change in the overall thicknesses of the upper Fossil Hill (= Merritton) and Rockway formations from the northern Appalachian to eastern Michigan Basin regions suggests that the Algonquin Arch did not influence regional sedimentation patterns during this time interval and that erosional phases were subdued prior to the transgressive phases that enabled deposition of the crinoidal shoal facies of the Irondequoit Formation.

## Irondequoit Formation (= basal unit of unsubdivided Amabel Formation)

The Irondequoit Formation is a crinoidal grainstone to packstone unit that possesses a fairly consistent thickness of approximately 3 m throughout the study area. It is a thick- to medium-bedded, medium grey to pinkish-grey, buff-weathering, dolomitic, brachiopod-rich encrinite. It possesses distinctive stylolites and thin styloseams sets reflecting short-lived time breaks. These styloseam sets and stylolites possess secondary pyrite, gypsum and pyrolusite in virtually every core in the Guelph area. These secondary mineral phases are a common feature of the Irondequoit Formation (*see* Brett et al. 1995). Encrinitic units may be separated by thin, greenish-grey argillaceous and micritic intraclasts. Intraclasts from the underlying Rockway Formation can be seen in the basal beds of the Irondequoit Formation above the welded contact.

This fine- to medium-crystalline encrinite-dominated package has been incorrectly assigned to the lower Amabel Formation (*see* Figure 25.4). It has been described as a low transmissivity zone of the lower Amabel Formation. The Irondequoit Formation rests disconformably below the overlying Gasport Formation with no Rochester Formation shales separating the 2 units (i.e., from just north of the Highway 401 through Guelph area). This upper contact is cryptic in nature and its exact position is difficult to assign from core to core. The most consistent features are a drastic increase in crinoid pluricolumnal size and associated increase in crystallinity and matrix colour and texture from Irondequoit Formation to Gasport Formation lithofacies due to the introduction of new and much larger crinoidal faunas.

## Rochester Formation

None of the cores in the Guelph region possess Rochester Formation shale lithofacies, demonstrating that variable episodic erosion of this rock unit had occurred, from northwestern New York State into southern Ontario, because of episodic movements in the forebulge, which resulted in cannibalization of unlithified or poorly lithified sedimentary units through time. The Rochester Formation pinches out just north of Hamilton and Cambridge, where it is approximately 1 m thick. Therefore, it does not act as a regional aquitard as observed in the hydrogeology investigations of the Niagara Escarpment between Niagara Falls and Hamilton (*see* Yager 1997, 2000). Details of the members of the Rochester Formation are outlined in Brett (1983) and Brett et al. (1995). Pinch-out of the Rochester Formation is partly a function of westward thinning of the siliciclastic lithofacies. However, near Hamilton, contacts within and at the top of the Rochester Formation clearly become erosional. Episodic uplift of the forebulge apparently resulted in cannibalization of unlithified or poorly lithified mixed calcareous–terrigenous muds and silts of this unit.

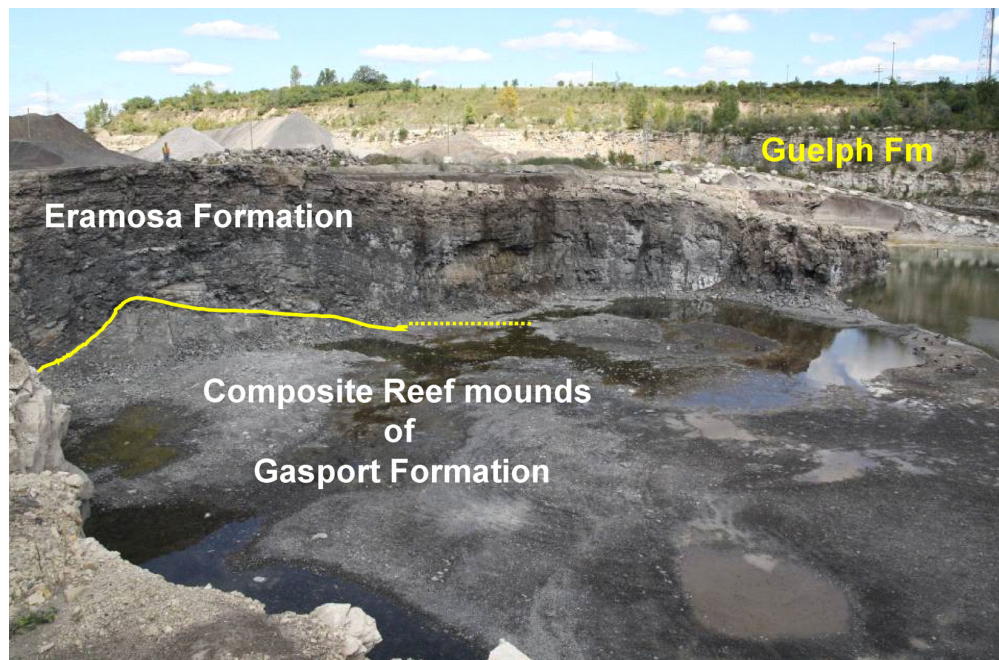
One of the most significant stratigraphic relationships discerned in the 2009 field season is that the Lions Head Member of the Amabel Formation (*see* Sanford 1969; Liberty and Bolton 1971; and Johnson et al. 1992) is a carbonate equivalent to the largely calcareous shales and dolostones of the Rochester Formation as known from outcrops between Hamilton and Niagara Falls. This is significant because it demonstrates that accommodation space was created on the far side of the ephemeral forebulge that resulted in deposition of horizontally bioturbated, finely crystalline dolostones with characteristic styloseam sets and intermittent chert development and pseudonodular fabrics. The Lions Head Member facies rest disconformably on the Irondequoit Formation crinoidal grainstones in every core on the Bruce Peninsula. This rock unit is also disconformably overlain by crinoidal grainstones of the Gasport Formation, which represent the main facies of the Amabel Formation (*see* Brunton 2008).

## Gasport Formation (= Warton and Colpoy Bay Members of the Amabel Formation)

The Gasport Formation consists of a basal cross-bedded crinoidal grainstone–packstone succession with incipient microbial–crinoidal reef mound lithofacies that change upward to rhynchonellid brachiopod–bryozoan–bivalve coquinas and large-scale microbial reef mounds dominated by crinoidal holdfasts and greater than 1 cm in diameter *Periechocrinites* sp. and possibly *Eucalyptocrinites* sp. pluricolumnals. The lower Gasport Formation, which represents a regional transgressive crinoidal succession, is generally a fine to coarse sand encrinite. In select areas where the crinoidal–microbial reef mounds form multiple stacked cycles, the thickness varies from 25 to more than 70 m. These stacked transgressive systems tracts (grainstone- and mound-dominated transgressive systems tract (TST) packages) make up the key hydrogeologic units in the Guelph–Cambridge region. Each cyclic package comprises a basal tan to white (bleached) encrinitic grainstone unit and upper dark blue-grey crinoid-dominated microbial reef mound. In the deeper subsurface of southwestern Ontario and Michigan (within Michigan Basin), this succession is known as the “White Niagaran” (*see* Figure 25.1).

The Gasport Formation represents the bulk of Amabel Formation lithofacies in the Guelph–Cambridge through Luther Lake region (*see* Figure 25.4; Photo 25.1). Detailed logging of rock core and key outcrops has shown that the relative thickness of the Gasport Formation controls the nature of overlying stratigraphic relationships throughout the study area. The changes in relative thickness of the Gasport Formation appear to be controlled by the accommodation space required to develop significant microbial–crinoidal–bryozoan–coral reef mound complexes. The thicker the Gasport Formation lithofacies and nature of composite reef mound growth, the younger the stratigraphic unit that rests disconformably on the sequence boundary. In areas where the reefal Gasport Formation exceeds 60 to 70 m in thickness, the Guelph Formation may rest disconformably on the Gasport Formation. There is no lithologic or diagenetic evidence to suggest that the older Goat Island Formation or Eramosa formational lithofacies were deposited and eroded prior to deposition of Guelph Formation lithofacies on the Gasport disconformity. Some of the cores display paleo-karstification of uppermost Gasport Formation reef mounds where it is overlain by Guelph Formation lithofacies. The amount of time represented by this time break is poorly constrained at present.

The Gasport Formation north of Hamilton and extending from Guelph to the southern Bruce Peninsula differs from the typical Gasport lithofacies in the Niagara Falls area in that it does not possess the inter-reefal Pekin member lithofacies that envelope the Gothic Hill member reef mounds. Gothic Hill member faunas and reef mound characteristics are reflected in the Wiarton and Colpoy Bay members of the Amabel Formation as outlined by Bolton (1953, 1957) and modified by Liberty and Bolton (1971) (*see* faunal lists in Williams 1919; Bolton 1957; Zenger 1965; Liberty and Bolton 1971). The sources of the argillaceous Pekin member lithofacies presumably were cut off by the migrating forebulge. This tectonically induced phenomenon enabled increased accommodation space and resultant thicker reef mound development on the leading edge of the forebulge in what is now referred to as the eastern Michigan Basin (north Cambridge to Guelph regions). Much of the Gasport Formation along the erosional edge of the Niagara Escarpment in the vicinity of Mountsberg through Mount Nemo to Duntroon areas and westward within the escarpment displays stacked crinoidal, brachiopod, bivalve and bryozoan skeletal megashoals with minor to no reef mound development (*see* Pratt and Miall 1993). These stacked complexes possess



**Photo 25.1.** Key outcrops in Guelph Dolime Quarry area that display the hydrogeologic character of the Gasport, Eramosa and Guelph formations (*see* Brunton 2008). No Goat Island Formation is evident at this outcrop exposure; the lower Eramosa Formation Vinemount member disconformably overlies the reef mound lithofacies of the upper Gasport Formation.

excellent to poor secondary porosity and permeability and karst-conduit development. Aquifer capacity or storativity within these inter-reef mound shoal complexes and composite reef mound facies appears to improve down dip or westward from the “disturbed zone” of the present-day escarpment margin zone (i.e., westward of the re-entrant terminations along the Niagara Escarpment).

The Lions Head Member of the Amabel Formation, which rests disconformably on the Irondequoit Formation in all cores drilled on the Bruce Peninsula, is a carbonate lithofacies equivalent of parts of the Rochester Formation. This recent discovery supports the contention to remove the Amabel Formation as a formal stratigraphic unit in Ontario (*see* Brunton 2008). The type section of the Amabel Formation in Wiarton may be used to characterize the key lithofacies packages of the Gasport Formation outlined in this report. In addition, the Wiarton roadcut also displays lithofacies best allocated to the Niagara Falls- and Ancaster-equivalent members of the overlying Goat Island Formation and a thin microbial-bearing phase of the basal Vinemount member of the Eramosa Formation.

## Goat Island Formation

The basal member of the Goat Island Formation is the crinoidal grainstone lithofacies of the Niagara Falls member (*see* Figure 25.4). This unit commonly has a distinctive pin-striped appearance and is finely crystalline and cross laminated. These encrinites range in thickness from a few metres to up to 10 m thick in the Guelph area. It is important to distinguish the coarse crystalline encrinites and reef mound lithofacies of the underlying Gasport Formation from the finer crystalline encrinites of the overlying Goat Island Formation (Niagara Falls member). The Niagara Falls encrinite has a distinctive lithochemistry: the Goat Island Formation lithofacies generally have elevated sulphates and halite relative to Gasport Formation encrinites. The Niagara Falls member is a relatively tight (lower hydraulic conductivity), cross laminated and finely crystalline crinoidal and brachiopod-bearing grainstone with incipient small reef mounds; it does not comprise the cliff-forming encrinites of the upper quarry face of the Old Nelson quarry on Kerns Road as reported in 2008 (Brunton 2008, p.31-10, also referred to as “Kern’s Quarry”). This encrinite package has a distinctive low conductivity and transmissivity response relative to the underlying crinoidal grainstones and coquinas that occur between microbial–crinoidal reef mounds of the underlying Gasport Formation. Niagara Falls member lithofacies represent the next transgressive pulse of the Silurian seaways across the significant paleotopographic relief created by the differential development of thick crinoidal–microbial reef mounds that characterize the Gasport Formation.

The overlying Ancaster member is a chert-rich, finely crystalline dolostone that is medium to ash-grey in colour, thin to medium bedded and bioturbated. It forms the cap rock of much of the Niagara Escarpment between Hamilton and Niagara Falls. This unit lies above the Niagara Falls member in roadcut exposures along the Niagara Escarpment from northern New York State to Hamilton. In the Guelph region, some of the cores display an interfingering of lithofacies of the Niagara Falls member and the Ancaster member. This intercalation of units, forming a kind of hybrid rock unit, occurs when the Gasport Formation is less than 30 to 50 m thick. Generally, the Niagara Falls member forms the basal crinoidal grainstone phase of the transgressive systems tract. Where the Gasport Formation is less than 20 to 25 m thick, the Niagara Falls member may be up to 10 m thick and the overlying Ancaster member up to 6 m thick. It can generally be predicted that where both the Niagara Falls member and Ancaster member lithofacies are present in cores, then thickened Eramosa Formation members, especially the presence of the basal Vinemount member, are also present.

## Eramosa Formation

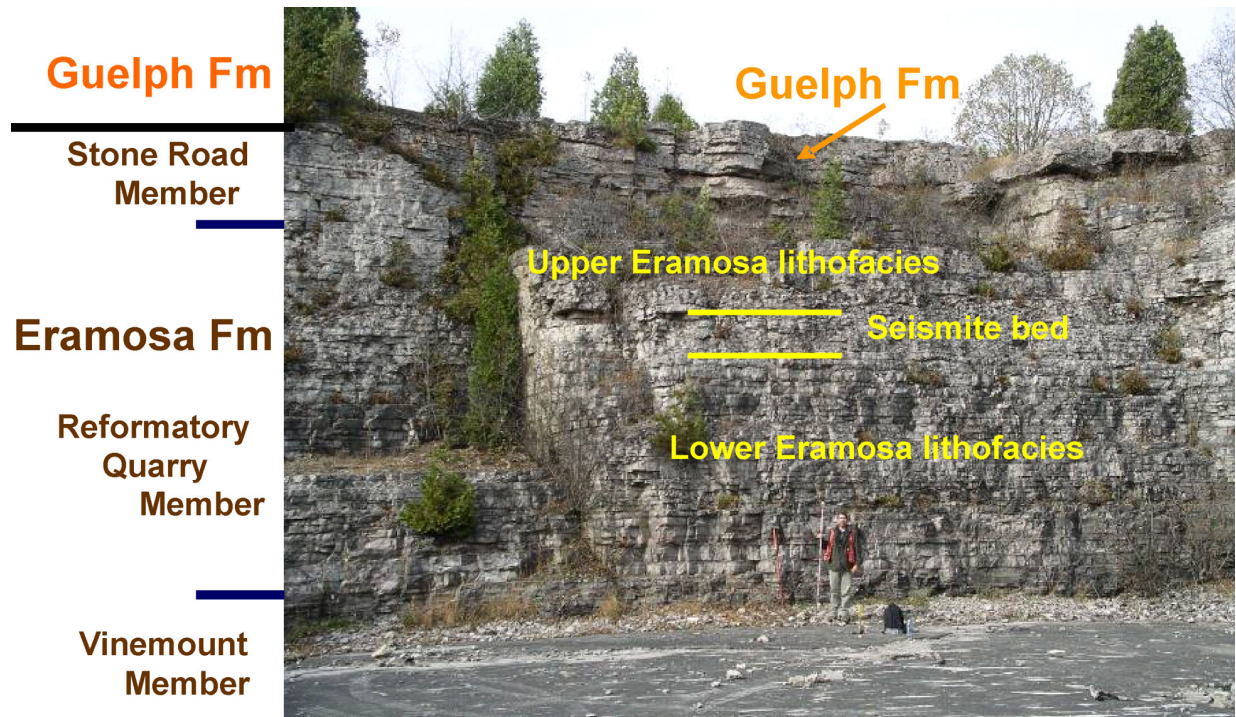
The Eramosa Formation is more laterally continuous along the Niagara Escarpment than is generally depicted in the literature (*see* Sanford 1969; Brett et al. 1995; Brunton and Dekeyser 2004; Brunton, Dekeyser and Coniglio 2005; Brunton, Armstrong and Dekeyser 2006). The regional scope of this study

further supports general use of formational rank for Eramosa lithofacies. Detailed field measurements have been made from more than 100 field stations, including stratigraphic sections from key outcrops, operational and abandoned quarries, and more than 60 rock cores spanning all or most of these cap-rock formations along the Niagara Escarpment. This work verifies the regional continuity and lithologic variability, and temporal significance of this rock unit. Therefore, this paper will refer to those lithofacies assigned to the Eramosa interval by Williams (1915a, 1915b, 1919), Shaw (1937), Bolton (1953, 1957), Sanford (1969), Telford (1978), Armstrong and Meadows (1988), Armstrong and Dubord (1992), Smith (1990), Tetreault (2001) and von Bitter et al. (2007) as the Eramosa Formation. Although key lithologic characteristics for this rock unit are provided below, a detailed description and proper definition of the Eramosa Formation, including the provision of a type section for both the Eramosa and Guelph formations, will follow in a future publication. Rock units recognized as members of the Eramosa Formation in this study differ from previous definitions of the Eramosa Formation by Shaw (1937) and Brett et al. (1995). Generally, only lithofacies that make up part of the Reformatory Quarry member described in this paper were incorporated into the previous definitions. This paper recognizes 3 members for the Eramosa Formation: Stone Road, Reformatory Quarry and Vinemount.

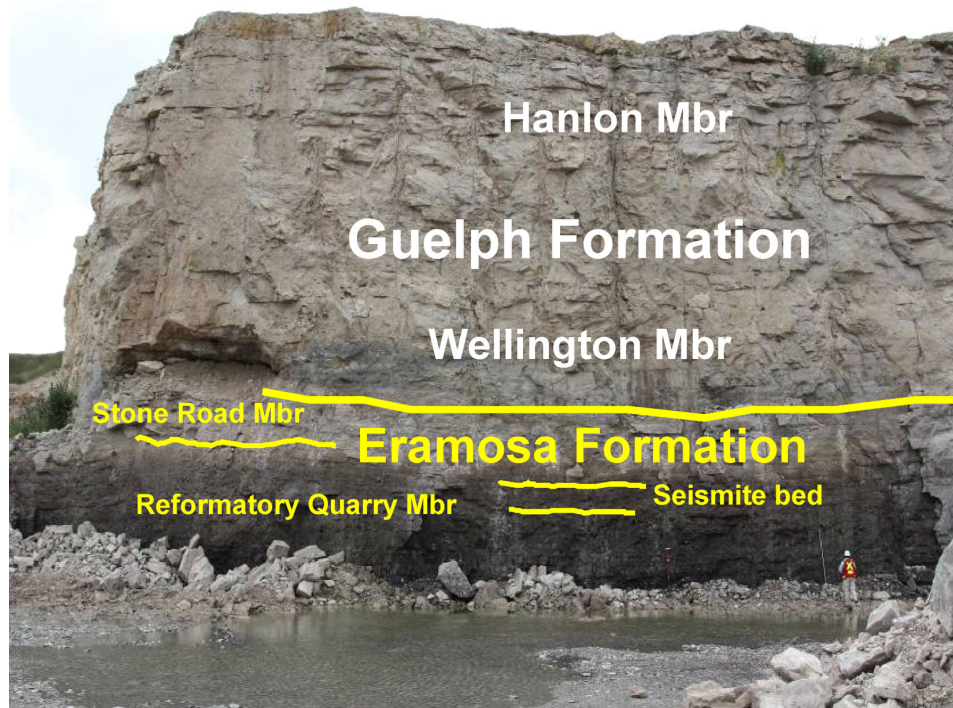
Detailed logging of the Vinemount Quarry and comparisons with City of Guelph, Cambridge and Bruce Peninsula cores reveal that the Vinemount beds, previously assigned to the upper member of the Goat Island Formation by Brett et al. (1995), actually correlate faunally and lithologically with lithofacies assigned to the Eramosa Formation in the Guelph through Warton areas (*see* Figure 25.1). Recent field work reveals that the Eramosa dolostones display significant regional variability in fossil content and sedimentary structures depicting abrupt temporal and spatial changes in depositional environments between the Michigan and Appalachian basins. The lateral discontinuity of these lower lithofacies has been the most challenging part of establishing a type section for this formation (Photo 25.2).

Lower Eramosa Formation lithofacies, previously named Vinemount Shale Beds or Vinemount beds, are herein referred to as the Vinemount member (*see* Figure 25.4). This rock unit averages 10 m in thickness when present in the Guelph region. It comprises thinly bedded, fine-crystalline, cyclic horizontally bioturbated traction current deposits with interbedded horizons rich in partially silicified diminutive *Whitfieldella* brachiopods and distinctive digitate tabulate corals (cladoporids) beds. The Vinemount member is most shaly in the vicinity of the Vinemount Quarry, east of Hamilton, and becomes less shaly west and northward away from the influence of the Appalachian foreland basin. These beds are black to dark grey in freshly cut core and blasted outcrops (e.g., Guelph Dolime Quarry, City of Guelph), but are a light grey colour in weathered outcrops. The distinctive petroliferous odour on broken samples verifies that it is Eramosa Formation. This lower succession grades upward into incomplete sabkha-like cycles and low-diversity coral biostromes that vary greatly in faunal and sedimentological character, regionally representing a restricted offshore marine setting.

There is a sharp contact between these lower lithofacies and the overlying, lighter brown to cream coloured thicker bedded, pseudonodular, coarsely crystalline and coral-stromatoporoid biostromal lithofacies of the upper Eramosa Formation. Although this contact is best illustrated in numerous cores from the City of Guelph, it is evident in 2 outcrops that form part of the same cuesta: the classic Guelph Railway cut section on the west side of the Eramosa River illustrated in Williams (1919) and the Reformatory Quarry section situated less than 0.5 km away on the east side of the Eramosa River (*see* Photo 25.2). These sections are situated just north of Stone Road where it crosses the Eramosa River, City of Guelph. The Reformatory Quarry and recently re-opened Guelph Dolime Quarry possess excellent exposures of the cream-coloured pseudonodular lithofacies of the upper Eramosa Formation. These upper dolostone beds are herein designated the Reformatory Quarry member and the Stone Road member of the Eramosa Formation (*see* Photos 25.2 and 25.3). Therefore, the type section for the Eramosa Formation, which will be formally described and published in the future, is proposed to be at the Reformatory Quarry in the City of Guelph (*see* Photo 25.2). The Reformatory Quarry member possesses a strongly deformed pseudonodular interval, herein interpreted as a seismite (earthquake-deformed bed) that varies in



**Photo 25.2.** Proposed type section of the Eramosa Formation, Reformatory Quarry, Guelph, Ontario. This abandoned quarry cuesta face enables the examination of the Eramosa Formation (Reformatory Quarry face and upper ostracod-dominated lithofacies, which occurs immediately below Guelph Formation lithofacies; Brunton 2008).



**Photo 25.3.** Key outcrops in the Guelph area display the nature of contact and hydrogeologic character of the Eramosa and Guelph formations (*see* descriptions in text; *see also* discussions in Brunton 2008). Photo is of the Guelph Dolime Quarry, south face. This outcrop exposure will serve as type section for Guelph Formation and alternate section for the Eramosa Formation.

thickness regionally (<30 cm to 1.6 m thick). It is mappable in well-exposed sections from the Niagara Gorge through Guelph to the Warton area of the Bruce Peninsula. The thickness of the upper member at the Reformatory Quarry member type section is approximately 5.5 m. The best complete exposure of the middle and upper members of the Eramosa Formation is in the Guelph Dolime Quarry, City of Guelph, but, because of active quarrying, the Reformatory Quarry is selected as the type section.

The Eramosa Formation is a very significant rock unit because it is a petroleum source rock and reservoir, a host of sulphide mineralization in the form of sphalerite, galena and pyrite, and, in part, acts as a regional aquitard between bedrock aquifers of the Gasport “unsubdivided Amabel” and Guelph formations. It also possesses exceptionally preserved soft-bodied biota that has been referred to as an exceptional Lagerstätte (*see* Tetreault 2001; von Bitter et al. 2007).

The Eramosa Formation is a most intriguing rock unit because, where exposed, it may display significant response to karstification due to its uniform fine dolomite crystallinity (e.g., Eramosa Karst, Stoney Creek; Buck, Worthington and Ford 2003). Where buried beneath Guelph Formation lithofacies or thick Quaternary clay tills and underlain by lithofacies of the Goat Island or Gasport formations, the more anoxic subtidal lagoonal mud-rich and microbial mat-bearing Eramosa lithofacies may act as an aquitard or aquiclude (Vinemount member). It separates overlying unconfined bedrock aquifers of the Guelph Formation from confined aquifers of the underlying Gasport Formation. It has been incorrectly referred to as a shale aquitard. The Eramosa Formation dolostone is interpreted as a largely deeper subtidal, low-oxygenated marine carbonate that shallows upward into shallow subtidal through marginal marine environments, with locally developed microbial–bryozoan–sponge mounds and favositid–stromatoporoid–bryozoan biostromes. The Stone Road member may prove to be a distinctive lithologic unit that is not present in many of the cores and outcrops that display the Eramosa–Guelph formational relationships.

The Eramosa Formation possesses a wide range of biologically and sedimentologically produced fabrics, including subtidal thrombolitic to laminar stromatolitic microbial mats displaying no evidence of subaerial exposure; to biostromal and small biohermal complexes possessing a low diversity bryozoan–microbial–coral composition to stromatoporoid–tabulate coral–bryozoan–microbial composition; to fine- to medium-crystalline, variably nodular and styloseamed wackestones and mudstones displaying evidence of varied horizontal bioturbation and storm deposition. Some rock outcrops in the Guelph to Rockwood areas display evidence of more open marine storm-influenced deposition, including features such as swaley cross-stratification (SCS) or possibly hummocky cross-stratification (HCS).

Whole rock geochemistry and microprobe analyses have revealed 3 phases of diagenetic pyrite formation. Elevated levels of arsenic occur within microbially precipitated, matrix-bearing, framboidal pyrites. This is a common occurrence in highly reducing pore water environments within restricted lagoonal microbe-rich environments. Elevated levels of lead from diagenetic galena, derived from basinal brines, are also detected in whole rock analyses. Galena preferentially occurs on vertical and horizontal joint seams and not as vug- or megafaunal skeletal-cavity fills, which is the preferred style for the various sphalerites.

The Eramosa Formation has been assigned an Early Ludlow age by Berry and Boucot (1970) and LoDuca and Brett (1991); a late Wenlock to early Ludlow age by Rickard (1975) and Norford (1997); and a Wenlock age by Stott et al. (2001). Recent work on the conodont biostratigraphy and carbonate carbon ( $\delta^{13}\text{C}_{\text{carb}}$ ) isotope stratigraphy of the Eramosa Formation reveals that the ages of these units are middle Sheinwoodian through possibly early late Sheinwoodian. The presence of *Ozarkodina sagitta rhenana* and *Kockelella walliseri*, combined with elevated carbonate carbon ( $\delta^{13}\text{C}_{\text{carb}}$ ) isotope values, indicates that this stratigraphic interval of the Eramosa Formation records the descending limb of the Ireviken Excursion (*see* Bancroft, Kleffner and Brunton 2008; Brunton, Bancroft and Kleffner 2008). This work confirms conodont studies by Stott et al. (2001) and von Bitter and Purnell (2005) from Eramosa lithofacies on the Bruce Peninsula. Therefore, the underlying Gasport and Goat Island successions are likely Early Wenlock in age. Further studies of the conodont biostratigraphy and carbonate carbon ( $\delta^{13}\text{C}_{\text{carb}}$ ) isotope stratigraphy of these formations are needed to confirm this age.

## Guelph Formation

The Guelph Formation comprises open marine medium to thickly bedded cross-stratified crinoidal grainstones and wackestones and lagoonal thinly bedded megalodont–gastropod-dominated wackestones and packstones, and lesser biostromal and biohermal reefal complexes. The Guelph Formation displays a sharp erosional basal contact with the underlying Eramosa Formation. This contact is characterized in outcrop and subsurface by a greyish-tan matrix with a discontinuous stromatoporoid–favositid biostromal package. Reef mound phases are present in the lower half of the formation and megalodontid bivalve and high-spired gastropod lagoonal cycles dominate the middle and upper parts of the succession. The top of the Guelph Formation is interpreted to be a significant erosional surface prior to the onset of increasingly saline basinal conditions that resulted in deposition of the dark algal-laminites and gypsiferous chocolate brown carbonates of the basal Salina Group.

The Guelph Dolime Quarry in Guelph has been chosen as the type section for the Guelph Formation (*see* Photo 25.3). Approximately 16 m of strata are well exposed in the upper quarry bench and display all key lithofacies of the Guelph Formation, including an excellent, sharp contact with the underlying Eramosa Formation. Good alternate sections can be seen in the Irvine Gorge section in Elora and key outcrops along the north shore of the Bruce Peninsula (between Cave Point and Tobermory). This stratigraphic unit possesses a cream to light brown matrix colour and is known regionally in the subsurface as the “Brown Niagaran” (*see* Sanford 1969). It is generally 15 to 22 m thick in the Cambridge through Guelph region and thickens toward Luther Lake and northern Bruce Peninsula regions where thicknesses exceed 60m. Although these lithofacies appear to conformably overlie bituminous, argillaceous, less fossiliferous dolostones of the Eramosa Formation (Brunton and Dekeyser 2004; Brunton, Dekeyser and Coniglio 2005; Brunton, Armstrong and Dekeyser 2006), preliminary conodont analyses and regional correlations of key tabulate coral and megalodontid bivalve megafaunal elements from the Bruce Peninsula and northern Moose River Basin and Arctic platform of Nunavut, suggest a latest Wenlock (Early Silurian) to early Ludlow (Late Silurian) age. The Guelph Formation represents an unconfined aquifer in the Guelph–Cambridge region of southern Ontario.

## SUMMARY AND FUTURE WORK

This paper provides proposed revisions to the Early Silurian sequence stratigraphic and sedimentologic framework and physical characterization of dolostone and calcareous shale rock units along the Niagara Escarpment of southern Ontario. The main focus of bedrock mapping and core logging during the 2008 field season was in the Guelph–Cambridge–Hamilton to Niagara Falls corridors. Additional drill core and key outcrop sections from the Bruce Peninsula, and Arthur and Luther Lake regions, located in the northern part of the study area, were also incorporated in 2009 to provide a more regional context to test the lateral facies changes within this revised sequence stratigraphic framework. The revised sequence stratigraphic framework will form the geologic foundation of a regional groundwater model that will address the vulnerability of groundwater resources required by Source Water Protection legislation and being completed under the Tier 3 studies of the City of Guelph and Kitchener–Waterloo Region.

Earlier studies delineated 2 bedrock aquifers known locally as the deeper Amabel “payzone” or “production zone” (representing coquinas and shoal complexes situated between reef mounds in Gasport Formation) and overlying Guelph aquifers and associated interface aquifers situated along the bedrock surface. However, the ability to predict the location and character of the water-bearing horizons and nature and distribution of the Eramosa aquitard unit, which separates the 2 main aquifers, has been difficult due to poor regional stratigraphic and sedimentologic understanding of the Silurian rock units (*see also* Brunton et al. 2007; Brunton 2008).

The establishment of a revised and testable sequence stratigraphic framework for aquifer and aquitard characterization was achieved during the 2008–2009 field seasons. Key sequence stratigraphic findings include the following:

1. the recognition of significant differential erosion on the Cabot Head Formation surface regionally;
2. the Reynales Formation does not extend very far into southern Ontario from New York State and those strata previously assigned to the Reynales belong to the younger Fossil Hill and Rockway formations;
3. the Merritton Formation dolostone (= upper Fossil Hill Formation), which disconformably overlies the Cabot Head Formation, Grimsby Formation and Thorold Formation surfaces, extends across the Algonquin Arch without significant change in thickness and character;
4. the Rockway Formation disconformably overlies the Merritton Formation and forms a persistent rock unit across the Algonquin Arch into the southern Bruce Peninsula region;
5. the Irondequoit Formation, previously unrecognized north of Hamilton in the subcrop–outcrop belt, rests disconformably on the Rockway Formation at a distinctive welded contact and has a consistent thickness across the Algonquin Arch and extends northward to Tobermory (previous stratigraphic and hydrogeologic investigations have placed this rock unit into the unsubdivided Amabel Formation);
6. the Rochester Formation shales, which pinch out just north of Hamilton and Cambridge areas, reappear as a finely crystalline dolostone (= Lions Head Member of Amabel Formation) on and just south of the Bruce Peninsula to Manitoulin Island region or to north of the forebulge region of the Algonquin Arch corridor;
7. the Gasport Formation, which consists of thick reef mound and inter-reef lithofacies in the subsurface of Cambridge–Kitchener–Waterloo and Guelph regions, is formally recognized as making up the majority of what has been traditionally called the unsubdivided Amabel Formation (comprising both the Wiarton and Colpoy Bay members of type section on Bruce Peninsula). A sharp, disconformable contact separates the Gasport Formation from the overlying basal crinoidal grainstone unit of the Goat Island Formation, known as the Niagara Falls member. This rock unit has been referred to locally in some hydrogeological reports as a low permeability unit of the unsubdivided Amabel Formation. The presence of significant paleotopography on the Gasport Formation is the main control on the character and presence and/or absence of overlying Goat Island and Eramosa strata along the Niagara Escarpment subcrop–outcrop belt;
8. the basal unit of the Goat Island Formation is known as the Niagara Falls member. It appears to exist in the type section of the Amabel Formation in Wiarton and along the northern coast of the Bruce Peninsula. This change is seen to be due to the rapid thickening of both Gasport and Goat Island formational encrinites over a distance of a few kilometres from Hamilton northward through the Guelph region to the Bruce Peninsula, coincident with the pinch-out of the Rochester Formation in the migrating forebulge region of the Algonquin Arch corridor;
9. the Ancaster member of the Goat Island Formation is generally found above the Niagara Falls member south of Hamilton, but interfingers with Niagara Falls member lithofacies in selected cores in the Guelph region and in more westerly cores of Michigan Basin in southern Ontario;
10. Eramosa lithofacies constitute a regionally persistent and faunally and lithologically distinctive rock unit that acts as a regional aquitard where the basal Vinemount member is present; therefore, it is recommended that the formational rank of the Eramosa be recognized more widely. Formal redefinition for the Eramosa Formation will be proposed and the formation will be subdivided into 3 members: a basal Vinemount member (main aquitard lithofacies), middle Reformatory Quarry member, and upper Stone Road member. The middle member possesses a distinctive seismite bed that is recognizable from Niagara Falls to the central Bruce Peninsula;

11. study of the contact between the Eramosa and Guelph rock units shows that the true level is higher than previously suggested and is marked by an erosional disconformity. The Stone Road member of the Eramosa Formation may prove to be a distinctive rock unit of formational rank upon further analyses.

Two key bedrock aquifers or hydrogeologic units are recognized in the Guelph–Regional Municipality of Waterloo area. The lowermost of these is the confined to semi-confined Gasport hydrogeologic unit (Gasport HGU), the character of which is influenced by the development of reef mound complexes and interbedded shell coquinas. These 2 lithofacies create discrete sequence-controlled enhanced hydraulic subunits within an overall regionally significant hydrogeologic unit. The second key regional bedrock aquifer is the unconfined Guelph hydrogeologic unit (Guelph HGU).

Preliminary hydrogeologic studies of selected boreholes reveal the presence of multiple high-volume water-bearing horizons where composite reef mound complexes are separated by shell-rich, bleached coquinas in the Gasport Formation. The recognition of both significant erosion at the top of the Gasport Formation and substantial changes in formation thickness associated with reef mound and coquina development over short distances (1 to 5 km) reveals that the paleotopographic relief of this unit is the main control for predicting both the presence of the Gasport hydrogeologic unit (Gasport HGU) and which unit will overlie this regional disconformity. Where the Gasport Formation is less than 30 to 50 m in thickness, Goat Island lithofacies (e.g., Niagara Falls member and/or Ancaster member beds) are present. Where Goat Island Formation strata occur above the Gasport Formation, they are overlain by both the Vinemount and Reformatory Quarry members of the Eramosa Formation. Eramosa lithofacies generally rest disconformably on the Gasport Formation when it is 50 to 70 m thick. The Eramosa Formation represents a regional aquitard, especially where shaly lithofacies of the newly established lower Vinemount member are prominent. In places where the Gasport Formation exceeds 60 to 70 m in thickness, owing to the establishment of thick reef mounds in the Early Silurian seaway, the Goat Island Formation and Eramosa Formation lithofacies are generally not present and the overlying Guelph Formation rests disconformably on the Gasport Formation. Detailed subsurface mapping of these lithofacies patterns, in conjunction with detailed hydrogeologic and hydrogeochemical studies using the FLUTE™ multi-level monitoring system (*see* Brunton 2008, p.31-3), hold the key to the eventual delineation of the Gasport and Guelph hydrogeologic units.

The main goal of this multi-year multi-disciplinary bedrock aquifer mapping program is to define and map out regional-scale groundwater flow systems that will lead to the delineation of discrete hydrogeologic units (HGUs). Such an approach will eventually enable calculations of groundwater volumes for the key Paleozoic-age bedrock aquifers across southern Ontario. These data will form the foundation for addressing fundamental questions concerning bedrock groundwater resources in southern Ontario in the context of changing climatic conditions and implications for long-term sustainability of these vital resources.

Preliminary data from this study suggest a disconnection of bedrock aquifers from surface water flow patterns away from the cuesta margin zone within the Grand River watershed and adjacent areas on the Bruce Peninsula and Manitoulin Island. The implications of such observations, once they are proven, may result in changes to how water budgets are defined for different areas of southern Ontario. The multi-disciplinary approach adopted in this study to evaluate and model the bedrock groundwater resources of the Niagara Escarpment will create a template that will be employed by the OGS to map and evaluate the groundwater resources throughout southern Ontario. The field-based methodologies developed for this four-year project will be applied to other regions of southern Ontario in order to develop regional bedrock aquifer maps for Devonian- and Ordovician-age strata. These maps and the resultant regional-scale estimates of groundwater volumes will then be used to estimate total available groundwater resources throughout southern Ontario and Manitoulin Island.

## ACKNOWLEDGMENTS

The compilation of stratigraphic units and regional correlations benefited greatly from conversations and field work carried out with Dr. Carl Brett (University of Cincinnati), Dr. Pat McLaughlin (Wisconsin Geological Survey and Natural History Museum), Daryl Cowell, and Dr. Mark Kleffner, Dr. Brad Cramer and Alyssa Bancroft (The Ohio State University). Constructive discussions with colleagues at the OGS, especially Derek Armstrong, concerning the evolving Silurian stratigraphy of the Niagara Escarpment were beneficial to the sequence stratigraphic framework presented. Discussions with John Petrie and John Piersol of Golder Associates Ltd. helped clarify and focus some of the regional bedrock hydrogeologic characteristics. Parks Canada staff Scott Parker and Cavan Harpur are thanked for their logistical support (use of boats) for the sequence stratigraphic studies along the northern Bruce Peninsula and nearby islands and for collaboration with karst studies on the Bruce Peninsula. Funding for this multi-year project is from the Ontario Geological Survey, the Ministry of Natural Resources (MNR), the City of Guelph Water Works Department and the Regional Municipality of Waterloo Water Services Division. Lastly, Candace Brintnell (The University of Western Ontario) is thanked for her able assistance and helpful discussions during the 2009 field season (*see* Brintnell et al., this volume).

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# 26. Project Unit 09-026. Characterization of the Fossil Hill–Cabot Head Formational Disconformity Between Tobermory and Guelph, Niagara Escarpment Region, Southern Ontario

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## INTRODUCTION

This report is derived from a student research project conducted in the summer of 2009 by the senior author to investigate the step-down removal of Early Silurian dolostone and mixed dolostone and shale above the Cabot Head Formation along the present-day eastern erosional limit of the Michigan Basin (Tobermory to Guelph). This research project will form the basis of a BSc (Hons) thesis at the University of Western Ontario. Although the stratigraphic interval of cores studied includes rock units that span the upper Medina, Clinton and Lockport groups of western New York and extending into southwestern Ontario from Niagara Falls to Hamilton (Brett, Goodman and LoDuca 1990; Brett et al. 1995), emphasis will be placed on descriptions of strata that comprise the Fossil Hill, St. Edmund, Wingfield, Dyer Bay, and uppermost Cabot Head formations. The key goal of the 2009 field season involved the integration of core and outcrop stratigraphic measurements and sedimentologic data on the Bruce Peninsula, extending southward to the Corbetton–Luther Lake areas, to establish the extent of lithologic variability and southernmost limits of these rock units along the main spine of the Bruce Peninsula, southern Ontario. The main OGS project incorporates and builds upon the major revisions to Early Silurian strata nomenclature and lithologic descriptions outlined in Brett et al. (1995) and proposed by Brunton (2008).

The revised stratigraphic framework outlined below would not have been possible without the availability of existing core from the Bruce Peninsula and more recent acquisition of more than 70 boreholes that have been drilled (50 cored) since 2004 and penetrate down to the regional aquitard of the Cabot Head shales (*see* Brunton 2008, and this volume). The average depth of the holes is approximately 100 m. Stratigraphic revisions were made on the following drill holes: 1) 6 holes cored from the top of bedrock (e.g., Guelph, Eramosa or Gasport formations) to either the Wingfield, Dyer Bay or Cabot Head formations on the Bruce Peninsula by the Ontario Geological Survey (OGS) in 1989 and 1990; 2) 2 OGS regional deep boreholes that extend from either the Guelph or Goat Island formations downward to Precambrian basement; and 3) 1 oil and gas drill hole that extends from the Gasport Formation through the entire Silurian succession (Figure 26.1). Additional drill core and key outcrop sections were measured at selected locations from the northern Bruce Peninsula (e.g., “clay cliffs” at Rocky Bay for the type section of the St. Edmund, Wingfield and Cabot Head formations; Dyer Bay Formation type section at Dyer’s Bay; and Inglis Falls) to Hamilton to provide a more regional context to test the lateral lithofacies changes within this newly proposed sequence stratigraphic framework (*see* Figure 26.1).

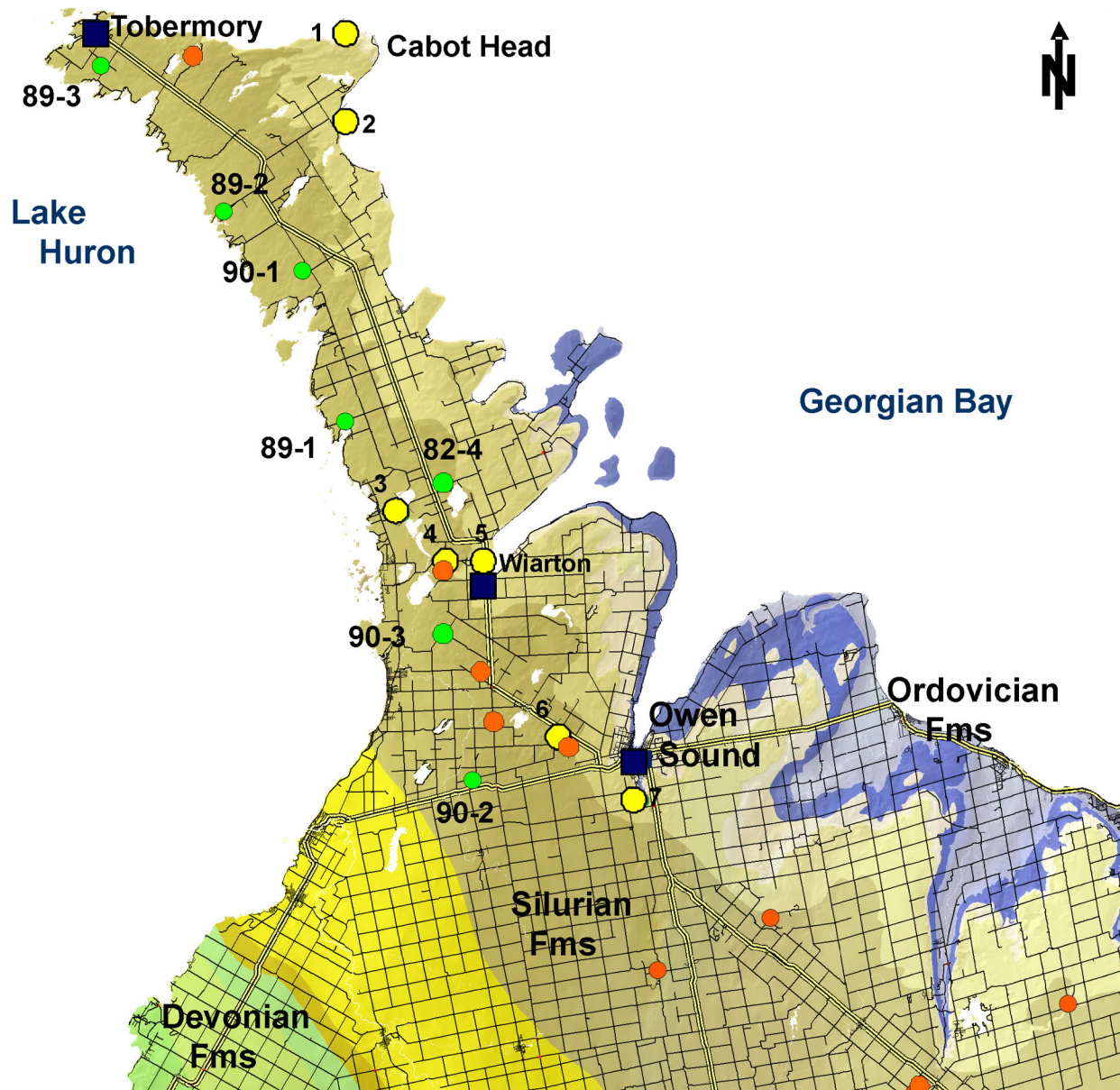
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*Summary of Field Work and Other Activities 2009,*  
*Ontario Geological Survey, Open File Report 6240, p.26-1 to 26-10.*

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## BACKGROUND AND SCOPE OF STUDY

Re-examination of core drilled by the OGS in the 1980s and 1990s and the addition of newly acquired core has provided an unprecedented opportunity to decipher the interplay between episodic tectonism, changes in accommodation space and associated sedimentation style related to ephemeral forebulge migration along the western perimeter of the Appalachian foreland basin during the Early Silurian. This



**Figure 26.1.** Bedrock geology and location map of key outcrops and core holes in Bruce Peninsula region, southern Ontario. Devonian sedimentary strata are coloured green; Silurian strata are yellow and tan; Ordovician strata are blue and grey. Yellow circles denote locations of key outcrops and are numbered 1 to 7: 1) Rocky Bay: type section for St. Edmund and Wingfield formations; 2) Dyer's Bay: type section for Dyer Bay Formation; 3) Sky Lake Eramosa formation section; 4) Ledgerrock Warton Quarry: Eramosa Formation and new drill hole; 5) type section for Amabel Formation (= Irondequoit, Gasport and lower Goat Island formations; *see* Brunton, this volume); 6) Ledgerrock Owen Sound Quarry: Eramosa Formation and new drill hole; 7) Inglis Falls roadcut: Cabot Head–Fossil Hill formational disconformity. Green circles represent OGS core holes used in study. Orange circles represent core holes drilled in fall of 2009. Blue boxes represent key towns within study area. The Luther Lake, Corbetton and Arthur areas mentioned in the text are to the southeast of the area shown in this figure,

interplay controlled the nature of the preserved strata between the northwestern Appalachian (Alleghany) and southeastern Michigan basins (*see* Brett, Goodman and LoDuca, 1990; Brett et al. 1995; Brunton 2008, and this volume).

This study builds upon recent geologic investigations in southern Ontario including 1) industrial minerals assessments of Silurian strata on the Bruce Peninsula; 2) a three-year mapping initiative to delineate karst of southern Ontario; 3) the three-dimensional mapping of bedrock aquifers in Early Silurian strata of the Niagara Escarpment (Brunton and Dekeyser 2004; Brunton, Dekeyser and Coniglio 2005; Brunton, Dodge and Shirota 2006; Brunton, Armstrong and Dekeyser 2006; Brunton et al. 2007; Brunton, Bancroft and Kleffner 2008; Brunton and Dodge 2008; Brunton 2008, and this volume); and 4) regional correlations of Early Silurian strata in western New York, Ohio and southern Ontario (Brett, Goodman and LoDuca 1990; Brett and Goodman 1996; Brett et al. 1998).

The main focus of the OGS study is to provide a revised Early Silurian sequence stratigraphic and sedimentologic framework and physical characterization of dolostone and calcareous shale rock units along the Bruce Peninsula, southern Ontario. Bedrock mapping and core logging during the 2009 field season was focussed in the Guelph–Cambridge–Sarnia through Bruce Peninsula corridors. Additional drill core and key outcrop sections from the Bruce Peninsula and the Arthur–Luther Lake regions will be incorporated to provide a more regional context to test the lateral facies changes within this revised sequence stratigraphic framework.

## EARLY SILURIAN STRATIGRAPHY OF BRUCE PENINSULA

As the main focus of this project, the strata described below include, in descending order, the Fossil Hill, St. Edmund, Wingfield, and Dyer Bay formations (Photo 26.1). These strata rest disconformably on the Cabot Head Formation shales (regional aquitard of the Niagara Escarpment) and are disconformable with the overlying Rockway and Irondequoit formations (generally covered by scree slope material in the northern Bruce Peninsula). These strata, in turn, are overlain by the Gasport and Goat Island formations, which form much of the majestic cliff faces of the Bruce Peninsula and the Niagara Escarpment (Photo 26.2). The OGS project incorporates and builds upon the major revisions to Early Silurian stratigraphic nomenclature and lithologic descriptions outlined in Brett, Goodman and LoDuca (1990) and Brett et al. (1995). The nomenclature adopted below for the Early Silurian stratigraphy of southern Ontario differs from that outlined in the *Geology of Ontario* volume (Johnson et al. 1992) and recent updates of the Paleozoic stratigraphy of southern Ontario (Armstrong and Carter 2006, p.17; Armstrong and Dodge 2007).

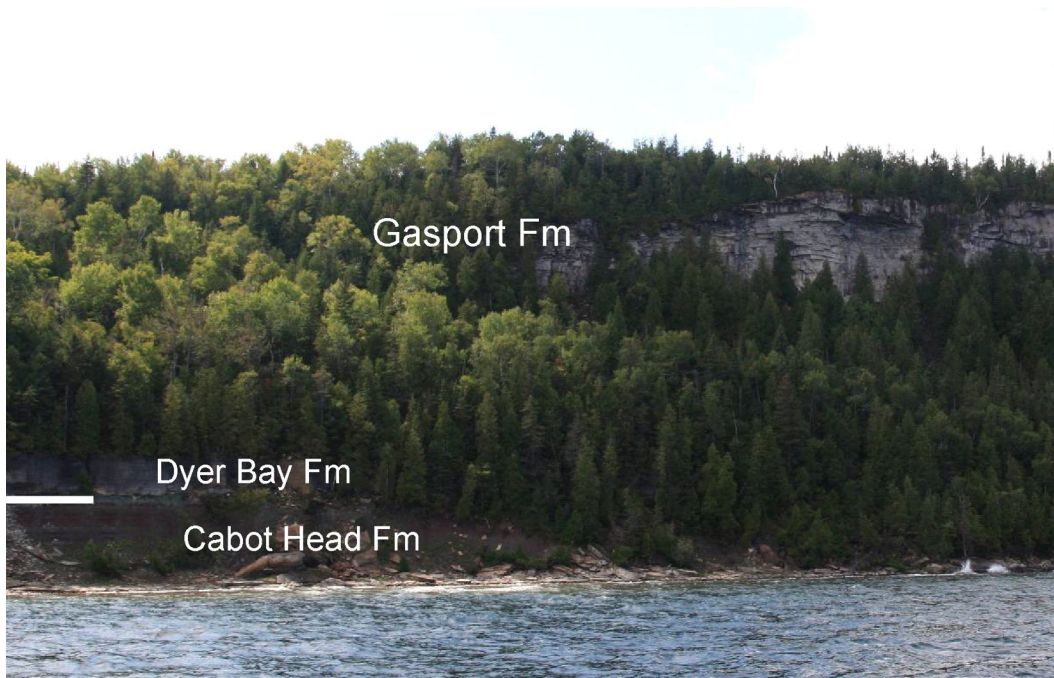
The type section for the Fossil Hill Formation is on Manitoulin Island, the remaining rock units of interest have type sections west of Rocky Bay (“clay cliffs” area) and Dyer’s Bay, northeastern Bruce Peninsula. The type sections were chosen for convenience and/or lack of other outcrops and do not necessarily reflect the extent of lithofacies characteristics observed in some of the core from the Bruce Peninsula.

### Cabot Head Formation

The type locality for the Cabot Head Formation, Wingfield Formation and St. Edmund Formation is the cliff exposure just west of Rocky Bay (also called “clay cliffs” area), east of Cabot Head, at the north end of the Bruce Peninsula (Grabau 1913; Bolton 1953, 1957; Liberty and Bolton 1971; *see* Photo 26.1). The Cabot Head Formation comprises grey to green to maroon, noncalcareous shale, with subordinate sandstone and carbonate interbeds (Bolton 1957; Johnson et al. 1992). The formation is generally poorly fossiliferous, although a few thin, bryozoan-rich shale and argillaceous limestone beds are known.



**Photo 26.1.** Type section of Early Silurian Cabot Head, Wingfield and St. Edmund formations, at the “clay cliffs” area, Rocky Bay, northeastern Bruce Peninsula.



**Photo 26.2.** Most westerly outcrop of the Cabot Head and Dyer Bay formations, northeastern Bruce Peninsula. This section highlights the generally covered interval of overlying dolostones and calcareous shales of the Wingfield, St. Edmund, Fossil Hill, Rockway and Irondequoit formations. The next significant bluff-forming rock unit is the Gasport and disconformably overlying thinly bedded encrinites of the Niagara Falls member of the Goat Island Formation (see Brunton 2008, and this volume).

Throughout much of southwestern Ontario, the Cabot Head Formation shale ranges from medium-bedded shales, separated by sharp contacts with overlying red bryozoan-bearing calcareous and noncalcareous mudstone units grading upward to greenish grey largely noncalcareous mudstones and dolomudstone to wackestone interbeds (cf. Sanford 1969). North of Grimsby, the Grimsby Formation grades into the upper Cabot Head Formation shale, which may be either green or red depending upon the amount of erosion on this disconformable surface. In the Bruce Peninsula area, a significant part of the Cabot Head Formation is red to maroon and possesses gypsum (indicating shallow-water to restricted marine environments).

The Cabot Head Formation is of varying thickness, ranging from a maximum of approximately 40 m under west-central Lake Erie, to approximately 12 m over the Algonquin Arch and then to over 36 m in the Owen Sound area (Sanford 1969). Some variation in thickness can be attributed to the uncertainty in picking its upper contact with the, in part, laterally equivalent Grimsby Formation, and its lower contact with the Manitoulin Formation. Also, toward the Algonquin Arch, the top of the Cabot Head Formation appears to be cut by a regional angular unconformity at the base of the Fossil Hill or Merritton formations (incorrectly referred to as the Reynales Formation). From Cabot Head to south of Owen Sound, regularly spaced boreholes reveal the removal or cutting-down of the middle and lower Fossil Hill Formation, and the underlying St. Edmund, Wingfield and Dyer Bay formations. This regional erosional event(s) has resulted in the Fossil Hill Formation (upper rock units = Merritton Formation) resting disconformably on either the Thorold, Grimsby or Cabot Head formations to south of Guelph through Niagara Falls region. In the Inglis Falls area to the south of Owen Sound (*see* Figure 26.1), the Fossil Hill Formation rests disconformably on the Cabot Head Formation. This is arguably the most significant disconformity in the Silurian succession of southern Ontario, representing several million years of erosion of strata. Preliminary observations of a few deeper cores on the Bruce Peninsula and Lake Erie region suggest that the Cabot Head Formation requires major stratigraphic revisions to integrate better the tectonostratigraphic history of the eastern Michigan and northwestern Appalachian basins as outlined in Brett et al. (1995). This will be the focus of future sequence stratigraphic studies that integrate the entire Early Silurian succession of southwestern Ontario and enable correlations around the Great Lakes region.

## **Dyer Bay, Wingfield and St. Edmund Formations**

The type locality for the Dyer Bay Formation is at Dyer's Bay, just south of Cabot Head, on the east coast of the northern Bruce Peninsula (Williams 1919; Liberty and Bolton 1971). The designation of discrete formational rankings for some of these rock units is problematic because greenish noncalcareous shales resembling that of the Cabot Head Formation are locally present above these dolostones (Dyer Bay and St. Edmund rock units), and mixed green shale with dolostone is locally present in the Wingfield Formation. From Clappison's Corners near Hamilton to Niagara Falls, upper Cabot Head Formation lithofacies are overlain by various sandstones and shaly siltstones of the Thorold and Grimsby formations.

### **DYER BAY FORMATION**

The Dyer Bay Formation was named by Williams (1919) and is known primarily from the Bruce Peninsula to Manitoulin Island region of the Niagara Escarpment. The upper contact of the Dyer Bay Formation is gradational to sharp with the Wingfield Formation (cores reveal a variable contact), and sharp and disconformable with any other unit (e.g., Fossil Hill Formation or Merritton Formation), although overlying units may be shaly and therefore difficult to distinguish geophysically. The distinctive medium to dark blue-grey, medium-grained texture of the Dyer Bay Formation distinguishes it from the tan to brown dolostones of the overlying carbonates or green to yellow (candy-striped) shales of the Wingfield Formation. It possesses a low-diversity coral and brachiopod fauna, is extensively horizontally bioturbated and displays well-developed ripple marks. In core from the Bruce Peninsula, this rock unit is

a predominantly blue-grey finely crystalline dolostone with grainstone storm pulses reworked with rip-ups from interbedded green shale partings. Minor crinoidal fragments and broken brachiopod shells are evident. Irregular hardgrounds with shell lags are common. The lowermost Dyer Bay Formation is a bioturbated brown mudstone with grainstone–packstone pulses. The Dyer Bay Formation is 2.5 to 3 m thick at its type section at Dyer’s Bay (Photo 26.3).

## WINGFIELD FORMATION

The first formal usage of the Wingfield Formation was by Williams (1937) for strata that are best exposed from Cabot Head to the designated type section west of Rocky Bay on the northern Bruce Peninsula (*see* Photo 26.1). The Wingfield Formation has a gradational to sharp upper contact with dolostones of the overlying St. Edmund Formation, or a sharp, disconformable contact with dolostones of the Fossil Hill Formation. The Wingfield Formation is more argillaceous than either the St. Edmund Formation or Fossil Hill Formation, and can be identified using geophysical logs in the subsurface. It is typically a greenish-grey to pink shaly mudstone to calcareous dolosiltite with typically darker brown dolostone beds than the overlying St. Edmund Formation. It is generally poorly fossiliferous and displays horizontal bioturbation. Some of the cores display a gradational relationship with the overlying brown finely crystalline dolostones of the St. Edmund Formation. Therefore, it is difficult to define the top of this formation. In core, it is predominantly a light to dark green shale with grey, finely crystalline dolostone interbeds. The upper Wingfield Formation is rich in green shales to small-scale shale–dolostone cycles displaying brecciated tops; some of the breccia textures may constitute possible caliche textures (marginal marine to soil conditions). The uppermost Wingfield Formation is a light tan-beige carbonate, horizontally bioturbated with intermittent reworked green shales and thinly laminated microbialites displaying possible dessication textures.



**Photo 26.3.** Type section of Dyer Bay Formation at Dyer’s Bay, northeastern Bruce Peninsula. The strata display a low-diversity favositid coral, bryozoan and brachiopod (*Virgiana*) fauna, extensive horizontal burrowing and well-developed ripple marks.

## ST. EDMUND FORMATION

The St. Edmund Formation was first described as a dolostone lens of the Cabot Head Formation (Williams 1919). It has a sharp upper contact with the overlying Fossil Hill Formation, but possesses a similar dolostone lithology and, therefore, is difficult to pick in borehole geophysical logs. These 2 units are very distinctive lithologically in core and the contact is always sharp and disconformable. The top is reported to be locally marked by a thin green shale bed that may produce a small gamma-ray spike (evident at type section west of Cabot Head; *see* Photo 26.1). This rock unit was designated a formation by Sanford (1978) and is equivalent to the Mindemoya Formation of Liberty (1968). The St. Edmund Formation is a finely crystalline dolostone, termed sublithographic or lithographic in older field descriptions. It possesses a sparse megafaunal component, but yields conodonts (P.G. Telford, personal communication, 2009). It is predominantly a medium- to dark-grey dolostone with centimetre-scale rhythmites, uniformly fine to medium crystalline with sparse green shaly partings and rip-up clasts. The lower St. Edmund Formation contains a correlatable coral-rich transgressive bed and a diagnostic intraformational conglomerate. A *Diplocraterion* marker bed is also common in the lower part of the formation.

## Fossil Hill Formation (= Merritton Formation, in part)

The type section for the Fossil Hill Formation is located on Manitoulin Island in a roadcut at the intersection of Highway 6 and New England Road, approximately 10 km southwest of Manitowaning (Bolton 1953, 1957; Winder 1961). Williams (1919, 1937) referred to this rock unit as the Lockport. This unit can be separated into lower, middle and upper parts based on faunal components and lithofacies. The lower unit possesses a brachiopod-rich succession with large pentamerid brachiopods in condensed beds, suggesting low sedimentation rates. The lower one-third to middle part of the formation, as revealed in the type section on Highway 6, consists of poorly fossiliferous lime mudstone to wackestone and superficially resembles the underlying St. Edmund Formation or Mindemoya Formation (termed the “false Mindemoya”). This “false Mindemoya” or St. Edmund Formation lithofacies is present in the northern cores on the Bruce Peninsula and thickens northward to the type section on Manitoulin Island. Hard grounds are present in this unit. The upper one-third of the Fossil Hill Formation shows a return to richly fossiliferous brachiopod beds of *Pentameroides* (not *Pentamerus*) and an abundant megafauna of tabulate corals and calcified sponges and related faunas. No bioherms have been described from this unit. The condensed nature and taphonomic character of the fauna in core indicates palimpsest conditions and a slow sedimentation rate. There are at least 4 significant disconformities in the Fossil Hill Formation at its type section on Manitoulin Island (*see also* Stott and von Bitter 1999).

The Fossil Hill Formation is very cherty and well indurated, which partly accounts for its regionally extensive nature. It is present from northern Michigan (where it is also known as the Manistique Formation) to Niagara Falls, where it is referred to as the Merritton Formation (Brett et al. 1995; Brunton 2008). Other good exposures of the Fossil Hill Formation are located on the Bruce Peninsula, on the shore of Isthmus Bay, just north of the village of Lion’s Head, and in a roadcut near Inglis Falls, just south of Owen Sound (Bolton 1957; Liberty and Bolton 1971; Armstrong, Goodman and Coniglio 2002; Armstrong and Carter 2006; Armstrong and Dodge 2007; *see* Figure 26.1).

The Fossil Hill Formation is everywhere disconformably overlain by the Rockway Formation (*see* Brunton, this volume) from the northern Bruce Peninsula to Niagara Falls. In general, the *Pentameroides*-dominated facies of the upper Fossil Hill Formation seems to be a regionally persistent rock unit (*see* Jin 2002). Of equal significance is the fact that the Irondequoit Formation is a persistent, thoroughly bioturbated crinoidal grainstone to packstone lithofacies that is present from Tobermory to Kincardine and in cores from the Chatham Sag area to Niagara Falls (Brunton, this volume).

The upper Fossil Hill (= Merritton) Formation rests disconformably above the Cabot Head Formation shale in cores from the Guelph area. It was originally identified as a member of the Reynales Formation (Kilgour 1963), which has produced some confusion in nomenclature. It is generally less than a metre thick and appears to thin to the east, towards the present-day cuesta margin. It is thicker in some cores in Guelph than at the type section in Thorold. It possesses the same pentamerid brachiopods and tabulates as the Fossil Hill Formation and is, therefore, correlated with that formation. It has been previously incorrectly assigned to the lower Reynales Formation of New York State, which is much older (Brett et al. 1995, p.31-34).

From the Luther Lake–Mount Forest area to Niagara Falls, this distinctive formation comprises up to 3 well-indurated beds of unequal thickness that are separated by dark, shaly partings (upper Fossil Hill = Merritton Formation). It has a distinctive, bioturbated, pinkish-brown finely crystalline matrix. It possesses a black, phosphate pebble-bearing hardground unit in the lower beds. The lower beds are wackestones, whereas the upper bed exhibits pentamerids (*Pentameroides subrectus*) and halysitid and favositid corals typical of the Fossil Hill Formation. The uppermost, brachiopod-rich beds are rarely evident in core from the Guelph region. *Planolites*-type burrows locally contain glauconite, and the lower beds are rich in pyrite.

## SUMMARY AND FUTURE WORK

Re-examination of core drilled by the OGS in the 1980s and 1990s and the addition of newly acquired core has provided an unprecedented opportunity to decipher the interplay between episodic tectonism, changes in accommodation space and associated sedimentation style related to ephemeral forebulge migration along the western perimeter of the Appalachian foreland basin during the Early Silurian. This interplay controlled the nature of the preserved strata between the northwestern Appalachian (Alleghany) and southeastern Michigan basins (*see* Brett, Goodman and LoDuca 1990; Brett et al. 1995; Brunton 2008). From south of Owen Sound to Niagara Falls, only the upper beds of the Fossil Hill Formation are preserved and rest disconformably on the Thorold, Grimsby or Cabot Head formations (Brunton 2008, and this volume). Cores collected systematically along the spine of the Bruce Peninsula and southward (from south of Tobermory to Corbetton) display a systematic cut-out of the middle and lower Fossil Hill Formation and underlying St. Edmund, Wingfield and Dyer Bay formations and upper green shales of the Cabot Head Formation.

A significant drilling program is currently underway (Brunton, this volume) to further test and refine the sequence stratigraphic framework of the Fossil Hill, St. Edmund, Wingfield, Dyer Bay and uppermost Cabot Head formations from the Beaver Valley region to the northern tip of the Bruce Peninsula. Based on the ground work conducted in the summer of 2009, the main goal of the BSc (Hons) thesis is to describe and outline the major changes in lithofacies character and nature of the systematic removal of these Early Silurian rock units from the northern Bruce Peninsula to areas south of Owen Sound. Such observations will be integrated with detailed lithogeochemical analyses of the stratigraphic succession (whole rock and trace element geochemistry, and carbon, oxygen and strontium isotopes). The significance of the 2 important disconformities below both the upper Fossil Hill Formation and the lower Fossil Hill Formation will be investigated further following the completion of the current drilling program taking place along the Niagara Escarpment (*see* Brunton, this volume).

## ACKNOWLEDGMENTS

This work constitutes part of a BSc (Hons) thesis by C. Brintnell at the University of Western Ontario, London, Ontario, under the supervision of J. Jin and F.R. Brunton.

Support for this multi-year project is from the Ontario Geological Survey, Ministry of Natural Resources (MNR), the City of Guelph Water Works Department, the Regional Municipality of Waterloo Water Services Division and Parks Canada.

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# 27. Project Unit 07-025. Ambient Groundwater Project: Grey–Bruce Counties and Area, 2009

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## INTRODUCTION

This paper presents the results of the 2009 Ambient Groundwater Project field work and the efforts to integrate the data collected so far on that project into a year-upon-year database. The Ambient Groundwater Project is an ongoing initiative of the Ontario Geological Survey (OGS) that started in 2007 to map the groundwater chemistry of southern Ontario and accessible regions of northern Ontario. High-quality groundwater geochemical data are being collected at a consistent sample density with the goal of mapping the baseline groundwater geochemical conditions in the major rock and overburden units. This will identify the geographic extent of natural chemical hazards in groundwater and reveal the relationship between rock–surficial sediment chemistry and water chemistry for the major water-bearing geological units in Ontario.

Analytical data from the first 2 years and field data from all 3 years are currently being integrated into a single year-upon-year database. Presented below are the results of integration of 2 of the over 80 parameters being determined: dissolved oxygen in bedrock wells and temperature in all drilled wells. Both show trends related to the geology of the area, the significance of which is also discussed below.

## 2009 STUDY AREA

The 2009 study area (Figure 27.1) encompasses approximately 10 000 km<sup>2</sup> and includes the northern part of southwestern Ontario from 10 km north of Goderich to the northernmost Bruce Peninsula. Samples from a total of 125 bedrock and 80 overburden wells were collected in this area in addition to 27 quality-control samples. A further 34 sites from the 2007 and 2008 study areas were re-sampled: 1) for isotopic studies on vapour-phase methane; 2) to test a temperature anomaly previously noted in the earlier data; and 3) as a year-upon-year quality-control check for a number of parameters including iodide.

Along with the 2008 and 2007 studies, the 2009 study completes the sample coverage of the western half of southwestern Ontario; an area that exceeds 30 000 km<sup>2</sup> in area (*see* Figure 27.1).

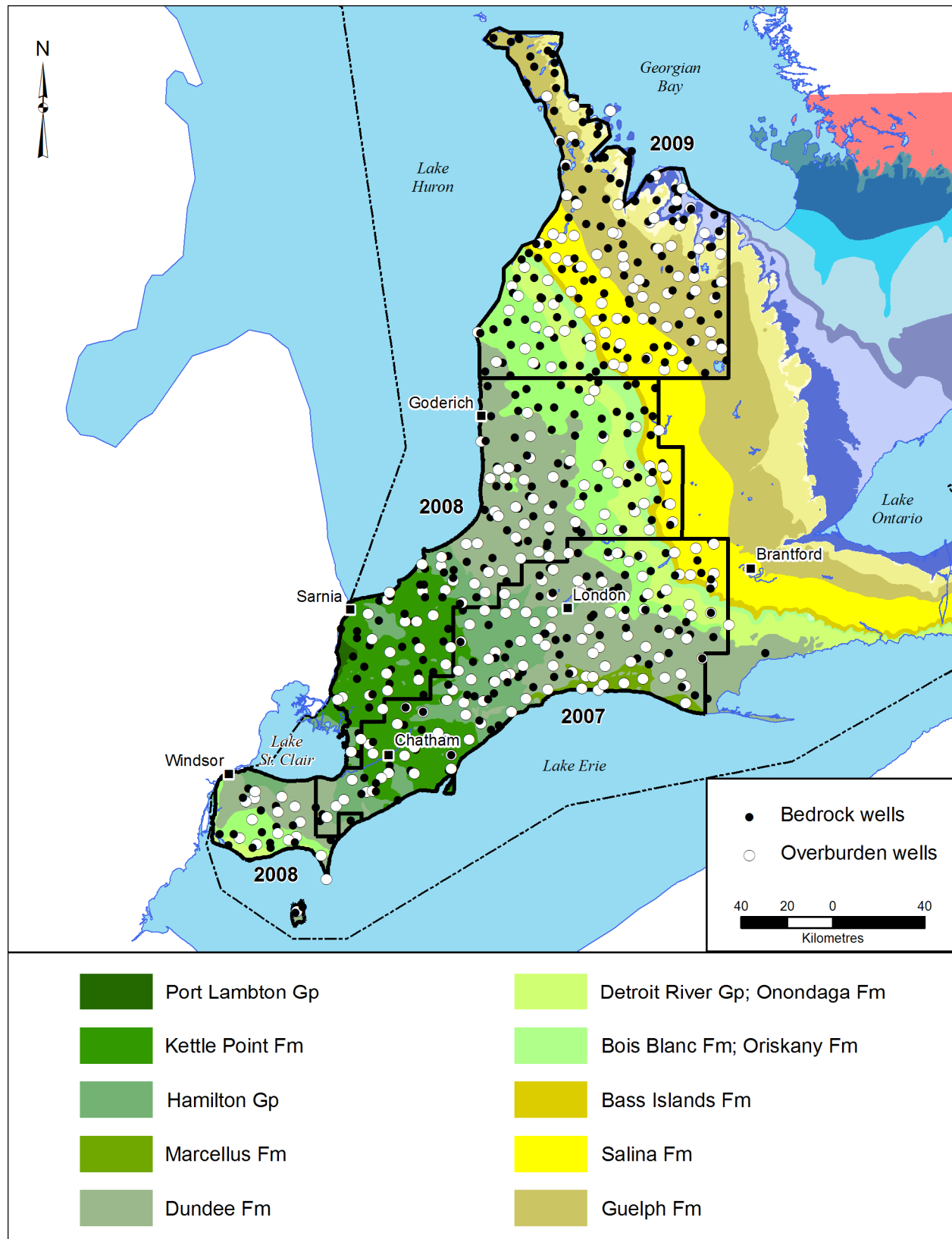
## METHODOLOGY

The Ambient Groundwater Program field methodology was described in Hamilton and Brauner (2008) and Hamilton, Brauner and Mellor (2007). Briefly, it involves sampling domestic wells on a regular 10 by 10 km grid. Using Ministry of Environment (MOE) well records, an overburden and a bedrock well are selected within each grid square or node, the homeowner is contacted and, once permission is received, the well is sampled using the existing domestic pump and distribution system from a sampling point that is ahead of any water treatment systems.

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*Summary of Field Work and Other Activities 2009,  
Ontario Geological Survey, Open File Report 6240, p.27-1 to 27-9.*

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**Figure 27.1.** Sample distribution for the 3 study areas completed to date (2007, 2008 and 2009). The top neat line around the Bruce Peninsula is the 2009 study area. Main bedrock formations underlying the study areas are illustrated on the figure.

At each site, notes are taken regarding the nature of the well and plumbing, the sampling point, the nature of the water (e.g., gaseous, odours, colour, turbidity, etc), and field-determined chemical and physical parameters including alkalinity and hydrogen sulphide are collected. Temperature, dissolved oxygen, pH, conductivity and oxidation–reduction potential are measured using a multiparameter instrument equipped with a flow-cell. During the initial purging of the well and domestic plumbing, these latter 5 parameters are continuously flow-monitored until they are stable or until long-term trends (up or down) are established that are deemed to be reflective of the nature of the groundwater and not due to incomplete purging of the plumbing. This usually involves purging at least 160 L and sometimes in excess of 400 L before sampling can begin. The parameters are logged during the entire sampling from the initial purging stage until all samples have been taken and measurements recorded.

The multiparameter instrument predominantly used in 2009 was a YSI<sup>®</sup> model 600LXM sonde with an Archer<sup>®</sup> hand-held field personal computer interface equipped with HydroPlusCE<sup>®</sup> logging software. This was intended to replace a Hanna<sup>®</sup> model HI9828 multiparameter instrument that was used in 2007 and 2008, but which experienced chronic problems with the pH electrodes. More than a dozen pH electrodes failed on 4 different instruments over the course of 2 years. All the other probes on the Hanna instrument performed superlatively, including the dissolved-oxygen probe, which has a standard Clark-Cell design. It also has a membrane system that is both easy to replace and foolproof, and is easily covered with a (homemade) cap to prevent attack by the frequently elevated H<sub>2</sub>S encountered in groundwaters.

The dissolved oxygen probe on the YSI also has a Clark-Cell design, but the membrane is more difficult to replace and impossible to individually cover in the event of high H<sub>2</sub>S. In 2009, following frequent H<sub>2</sub>S-related failures of the YSI dissolved-oxygen probe, both multiparameter probes were used during sampling: the YSI to collect pH, conductivity, redox and temperature, and the Hanna to collect dissolved oxygen and temperature. The 2 instruments had similar levels of precision and accuracy for all the parameters. If significant H<sub>2</sub>S (>0.1 ppm) occurred in the water being sampled the dissolved-oxygen probe was capped for protection and dissolved oxygen was recorded as zero for that site. Dissolved oxygen (DO) and H<sub>2</sub>S are incompatible in solution for any more than a few minutes and, therefore, groundwaters naturally containing H<sub>2</sub>S have no dissolved oxygen.

After field work, the multiparameter logs were examined to determine how well they represent actual groundwater conditions. In the 3 years of sampling, 643 logs were collected. Temperature is the most reliable indicator of stability and an examination of the logs showed that in 76% of cases, temperature readings were stable or nearly stable by the end of the measurements. The remainder were either deleterious for various reasons, or showed an upward or, more often, downward trend due often to the continuous high rate of pumping that changed storage conditions in the well. Changes in chemistry due to changing storage conditions in the well is one of the potential biases that can occur when sampling domestic wells, but, fortunately, it does not happen often in drilled wells. Large diameter bored or dug wells, which typically have high storage capacity but often low rates of inflow, are much more susceptible to this bias.

Temperature is a bellwether parameter, the stability of which is a good indicator that fresh water is being obtained from the well. However, an unstable temperature does not always indicate that the plumbing has been incompletely purged or that the chemistry of the groundwater is changing. For example, a slow temperature drop may indicate heat input during the cooling of long supply lines and plumbing and this is not likely to significantly influence the chemistry of fresh well water. In cases where the temperature is unstable, the logs of the chemical parameters (pH, conductivity, DO and ORP) must then be examined for stability. If unstable, it should be noted that that incomplete purging may have occurred or that the chemical character of water from the well may have changed during sampling. This can result in less-representative groundwater chemistry and lead to problems during quality control such as electrical charge imbalances between cations and anions (due to their respective bottles being filled at different times during the sampling).

Although the temperature probes for the Hanna and YSI instruments have equally good accuracy ( $\pm 0.15^{\circ}\text{C}$ ) and resolution ( $0.01^{\circ}\text{C}$ ), the methodology of measuring groundwater temperature after pumping through a domestic plumbing system must inevitably add a positive bias to the temperature of the groundwater. A field experiment was carried out to determine the difference between apparently stable temperature readings measured in a flow cell and the actual *in situ* groundwater temperature. A Levellogger<sup>®</sup> Gold down-hole temperature and pressure datalogger was used to determine *in situ* groundwater temperature to an accuracy of  $\pm 0.05^{\circ}\text{C}$  with a resolution of  $0.003^{\circ}\text{C}$ . Prior to measurement, the difference in accuracy of the YSI relative to the Levellogger was determined to be  $0.23^{\circ}\text{C}$  and this was subtracted from all subsequent YSI readings. This effectively rendered the relative accuracy of the 2 instruments to be the same as their poorest precision (i.e.,  $\sim$  the YSI resolution of  $0.01^{\circ}\text{C}$ ).

The Levellogger was lowered in turns down 7 wells that were being sampled and temperature data were recorded at 5 second intervals during the same period and at the same sample interval that measurements were being made with the YSI and flow cell on surface. One of the 7 wells was a dual system with 2 wells. All such systems necessarily have additional plumbing and usually have large holding tanks and, therefore, are unsuitable to be used to derive groundwater temperatures. Also, this type of system is usually avoided as part of the ambient groundwater protocol, but was occasionally sampled where wells were difficult to find in some nodes. The other 6 sites were typical single-well domestic systems with pressure tanks. All wells tested were equipped with down-hole submersible pumps.

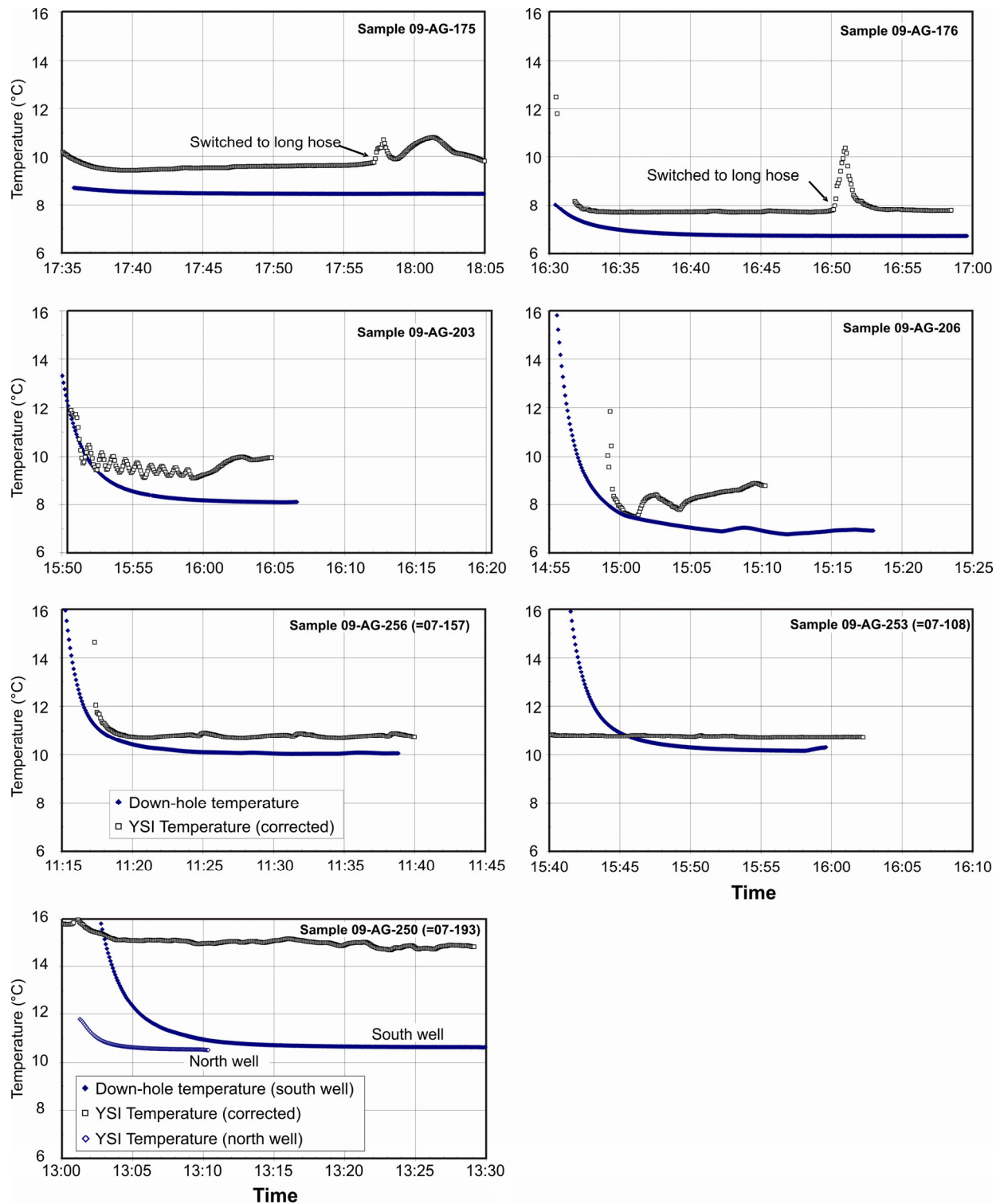
## PRELIMINARY RESULTS – OXYGEN AND TEMPERATURE

Figure 27.2 shows the results of the temperature experiment. Surface flow cell results for all wells are warmer than actual *in situ* temperatures. The difference between the stable *in situ* reading and the flow cell reading was determined and, where the surface measurements were not completely stable, the lowest surface temperature was used. In the order shown on the figure, the differences for the 6 typical wells (in  $^{\circ}\text{C}$ ) are 0.97, 0.98, 0.99, 0.73, 0.56 and 0.67 with an average of  $0.82^{\circ}\text{C}$ . The well with a mixed distribution system showed a  $4.0^{\circ}\text{C}$  temperature increase resulting from heat gained in the distribution system. This is despite the fact that the homeowner had been intensively using water for most of the morning prior to our testing. The 2 wells that source this system are both finished in overburden and at roughly similar depths of about 16 m. The temperature probe in the south well was installed 1 m from the bottom, whereas, in the north well, it was installed about half-way down, hence its slightly lower temperature. The results show that the positive temperature bias from domestic wells is, for the most part, consistently below  $1^{\circ}\text{C}$  and supports the standard methodology of the ambient groundwater program, which avoids mixed distribution systems except where no other wells are available.

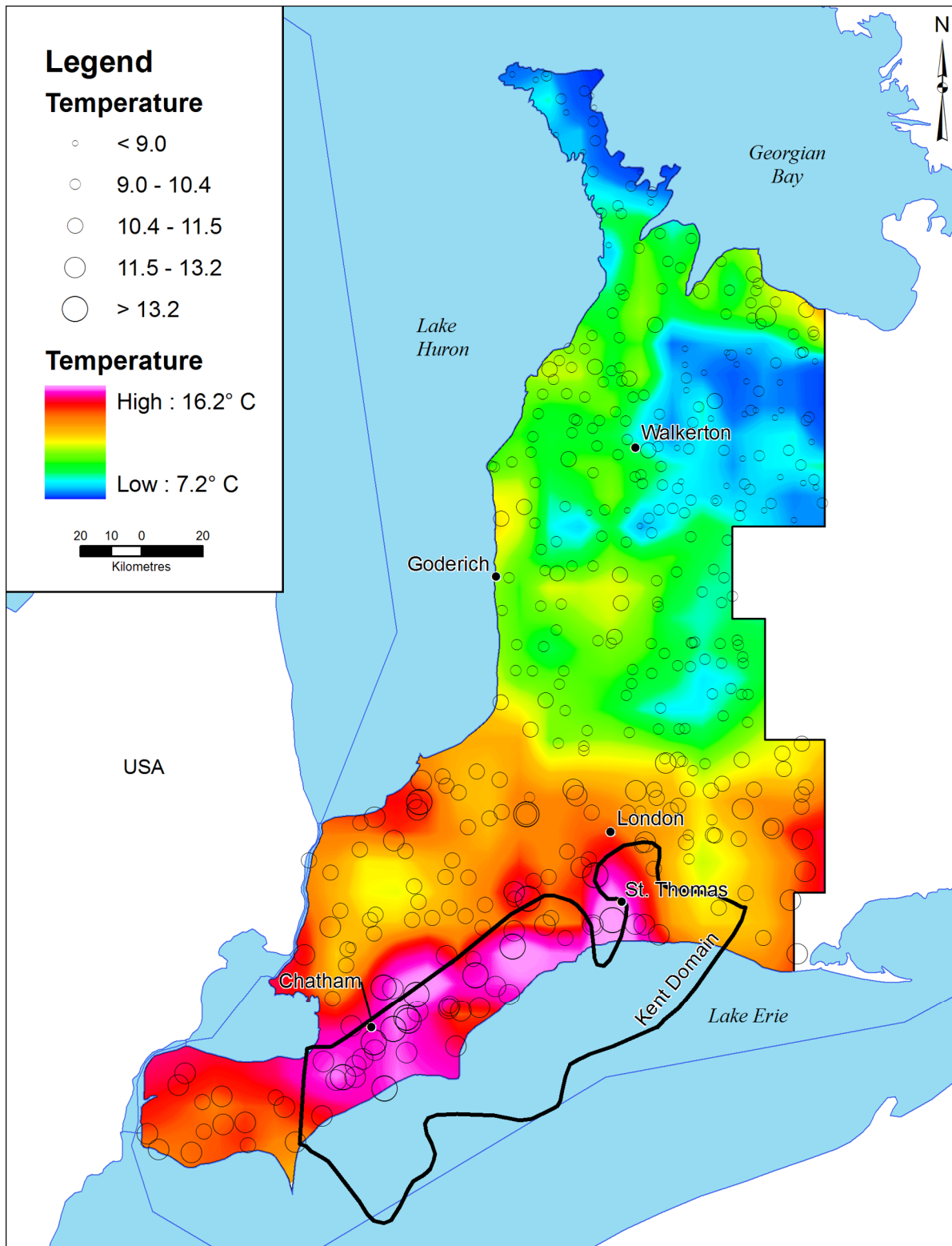
Figure 27.3 shows a plot of raw temperature of groundwater extracted from drilled wells exceeding 15 m in depth for all 3 study areas as measured in a flow cell. Data are only included for sites where

1. A temperature log exists and the temperature trend was stable or nearly stable.
2. The purging volume and rate were within the normal range for the program.
3. Wells were narrow, 15 to 20 cm (6 to 8 inches) diameter, and drilled, not bored or dug.
4. The standard sampling and measurement methodology were followed.
5. Wells were not distal to the sample collection point (where recorded).

Numerous trends and anomalies are apparent in the temperature data for overburden and bedrock wells whether they are plotted as individual data sets (not shown) or together (*see* Figure 27.3). The data from the Bruce Peninsula in the north show the coolest temperatures of the study area, particularly in its eastern half. The highlands in the northeast show distinctly colder temperatures that warm abruptly to the



**Figure 27.2.** Temperature measurements made using a YSI multiparameter meter and flow cell according to the standard ambient groundwater program versus measurements made *in situ* with a down-hole temperature logger. The top 6 logs were recorded on wells with typical plumbing that are the type normally sampled in this program. The bottom-most measurements (well 09-AG-250) are from a dual well system and holding tank, which is a system normally avoided. Using the flow cell, stable readings are reached within 10 minutes. The first 2 logs (09-AG-175 and 176) show that using the 15 m long sampling hose has a relatively minor effect on temperature when compared with the results for the short (2 m) hose, except that reaching stable readings takes an additional few minutes.



**Figure 27.3.** Flow-cell measurements of raw groundwater temperature from drilled wells (both overburden and bedrock) exceeding 15 m in depth for the 2007, 2008 and 2009 study areas. It should be noted that the domestic pumps and distribution systems by which these groundwaters were sampled add an average of 0.8°C to the final temperatures reported here. As a result, *in situ* groundwater temperatures are likely to be lower by about that factor. The dark outline on the shore of Lake Erie is the boundary of the Proterozoic Kent plutonic domain beneath the Paleozoic sedimentary rocks (Easton and Carter 1995).

north below the Niagara Escarpment in the Beaver Valley–Owen Sound area and gradually to the west and south as elevation decreases. The sudden change to warmer temperatures across an east–west line in the south-central part of the study area is less easy to explain, as is the very significant positive temperature anomaly that extends from 20 km west of Chatham to approximately St. Thomas. This anomaly encompasses at least 3000 km<sup>2</sup> and is several degrees warmer than the 11°C background temperature in adjacent areas. It is spatially associated with the underlying Precambrian Kent plutonic domain, which is largely comprised of granodiorite (Easton and Carter 1995; outline on Figure 27.3) and is buried beneath more than a kilometre of Paleozoic sedimentary rock. Further investigation will be required to determine if the elevated temperature in this area is due to increased radiogenic heating from this underlying domain or to other reasons such as elevation and localized climatic conditions.

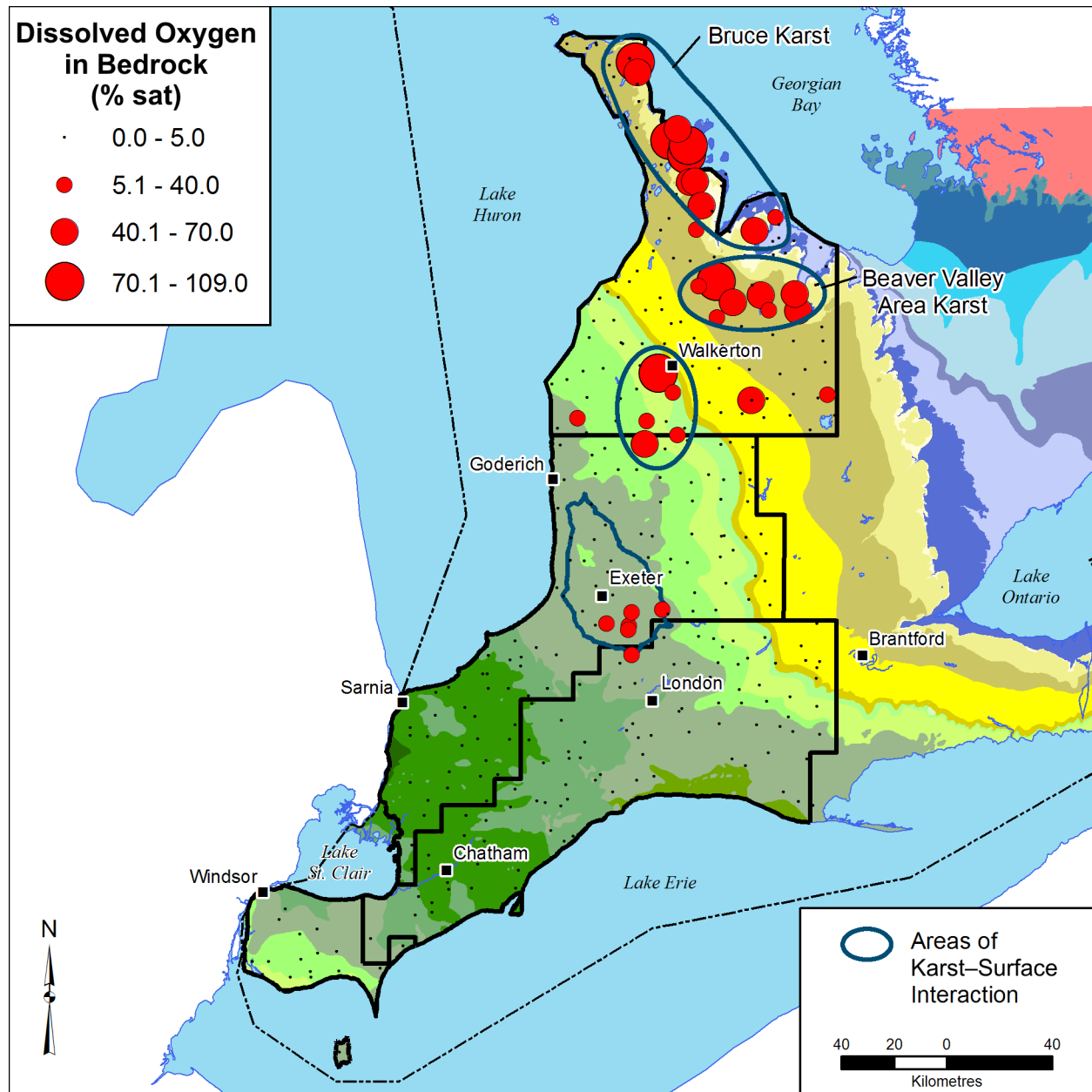
Figure 27.4 shows dissolved oxygen in groundwater extracted from bedrock wells throughout the 3 study areas. Dissolved oxygen in bedrock groundwaters in Canada is relatively limited in extent due to its consumption during recharge through the extensive Quaternary glacial sedimentary cover and along the groundwater flow-path through unweathered bedrock. Organic materials in both overburden and sedimentary rock contribute to this oxygen consumption as do the hydrogen sulphide and methane that are common in southwestern Ontario aquifers. Of the 349 reliable dissolved oxygen measurements in bedrock, only 40 had detectable dissolved oxygen and most of these occur in the northern half of the study area in areas of known karst development. Data from the study areas completed to date show 4 regions with widespread dissolved oxygen in groundwater (*see* Figure 27.4). These are the eastern Bruce Peninsula, the Beaver Valley area; the Walkerton area and an area of “breathing wells” centred on the town of Exeter.

In southwestern Ontario, high dissolved oxygen (*see* Figure 27.4) and cold groundwater temperatures (*see* Figure 27.3) appear to be associated with areas of extensive subsurface karst. Karst in the Amabel Formation (F.R. Brunton, personal communication, 2009) on the eastern half of the Bruce Peninsula is widely identified in both surface outcrops and the subsurface in this area (Brunton and Dodge 2008). Anecdotal evidence from the 2009 field season for this area includes the report of a cave crayfish being washed to surface in the cuttings during the drilling of one of the domestic wells we sampled. This was one of the many bedrock wells in the region with water that exhibits high dissolved oxygen (95% saturation) and cold temperatures (8.5°C). The Beaver Valley area (*see* Figure 27.4) is also known to host extensive karst terrain and it appears from both the temperature and oxygen data that its subsurface extent is much larger than is visible on surface. The dissolved-oxygen anomaly in bedrock covers an area of at least 700 km<sup>2</sup>, trends westward from the Beaver Valley area and is all the more remarkable since the water-bearing zone occurs at an average depth of 33 m with an average of 20 m of overburden cover. The negative temperature anomaly associated with the dissolved-oxygen anomaly is the coldest measurement of the three-year study with the exception of the eastern Bruce Peninsula.

Another area of karst, centred on Exeter, encompasses approximately 1395 km<sup>2</sup> and has been known for many years by well drillers (R. Hopper, W.D. Hopper Well Drilling Limited, personal communication, 2009) as an area of breathing wells. Breathing wells (also known as ‘sucking and blowing’ wells) take in and exhale large quantities of air when the well caps are removed. This can create problems in winter because water pipes can quickly freeze if the well cap becomes unsealed. Whether the wells are sucking or blowing depends on atmospheric pressure conditions at the time and can remain in that phase for a number of days. The widespread nature of this phenomenon and the very long phases of sucking and blowing suggest an enormous unsaturated reservoir above the water table. All these wells are unusually deep (>100 m) and have static water levels that are close to the depth of the well. The unsaturated cavities appear to be in the Devonian Lucas Formation immediately where it underlies the Dundee Formation; further work will be required to confirm this.

When the breathing wells are allowed to suck, the air that enters them has atmospheric levels of oxygen (21%). However, preliminary measurements made on the exhaled gases during the blowing

phases indicate oxygen is highly depleted and is likely absent in many of the wells. The dissolved oxygen in bedrock groundwater reflects this. An area of approximately 400 km<sup>2</sup> in the south of the region shows depleted but measurable dissolved oxygen with an average of 19.1% saturation (100% saturation would be expected if the water was in contact with atmospheric levels of oxygen). In the remainder of the region, dissolved oxygen is absent from the well water. The propensity of the aquifer to absorb oxygen is intriguing and is the subject of a MSc thesis by the second author. It also has major health-and-safety implications since wells in the blowing phase could fill a well hut or basement with oxygen-free air in just a few minutes; creating a potentially deadly scenario.



**Figure 27.4.** Dissolved oxygen in bedrock. Oxygen in groundwater from wells drilled into bedrock was detected in only 11% of wells sampled in the three-year study. Most of these wells occur in 4 clusters associated with karstic conditions in bedrock. The area outlined around Exeter defines a region of ‘breathing wells’ as describe in the text. The extent of this area was mapped, and kindly provided to the OGS, by R. Hopper of W.D. Hopper and Sons Limited.

In addition to lower dissolved oxygen, the breathing well region also lacks a significant negative temperature anomaly, but this is likely due to the unusually deep nature of the karstic system. Almost all the wells exceed 100 m in depth and the temperatures seem to reflect this. The temperatures in the breathing well region are on average somewhat higher than the area, immediately to the east.

Finally, a zone of bedrock wells in the general vicinity of Walkerton also exhibits positive dissolved oxygen. Surface karst topography has not been documented in this area, but conditions of “groundwater under the direct influence of surface water” (GWUDISW) are infamous in the Walkerton area. The dissolved oxygen values suggest karstic conditions or at least the presence of solution-enhanced jointing. The large, but albeit discontinuous, extent of this dissolved-oxygen anomaly suggests that possible “groundwater under the direct influence of surface water” conditions may exist in the aquifer at a considerable distance from the town of Walkerton. Examination of oxygen levels in the overburden well water (not yet done) sampled in this area will help to determine if this is a continuous karst system or just localized solution-enhanced jointing in the shallow rock strata.

## ACKNOWLEDGMENTS

The authors would like to thank Ron Hopper of W.D. Hopper Well Drilling Limited for sharing his considerable knowledge of the hydrogeology of the 2009 study area and in particular for providing us with a detailed map of the extent of breathing wells in the Exeter area. Excellent and very professional field assistance was provided by Kevin Little, Alyne Lalonde, Ryan Mariotti and April Bertrand.

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# 28. Project Unit 09-025. Mine Centre Area High-Density Lake Sediment and Water Survey, Northwestern Ontario

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## INTRODUCTION

Field work for a high-density lake sediment and water geochemical survey of the Mine Centre area, in northwestern Ontario, was carried out between July 27 and August 25, 2009. The survey area is centred on the village of Mine Centre, which is located approximately halfway between the towns of Atikokan and Fort Francis in northwestern Ontario (Figure 28.1). The survey completely covered the area defined by National Topographic System (NTS) 1:50 000 scale map sheets 52 C/10, 52 C/15, 52 C/16, 52 F/1, 52 F/2 and partially covered the area outlined by map sheets 52 B/12, 52 C/1, 52 C/7, 52 C/8, 52 C/9, 52 C/11 and 52 C/14. This survey area covers rocks with known exploration potential for gold and base metals (e.g., Bad Vermillion Lake), and also areas with relatively unknown potential (e.g., Quetico Subprovince metasedimentary rocks).

A total of 1729 water samples and 3099 lake sediment samples were collected over an area of approximately 5700 km<sup>2</sup>. The 3099 sediment samples comprise 1632 shallow samples (<15 cm sediment depth) and 1467 deep samples (>15 cm sediment depth). The total of 1729 lake sites visited corresponds to an average density of 1 sample site per 3.4 km<sup>2</sup> of area. This survey is the first high-density regional lake sediment geochemistry coverage to be completed over the region. This study area was previously sampled at a lower density (1 sample per 12 km<sup>2</sup>) during the National Geochemical Reconnaissance (NGR) lake sediment program carried out in 1979 by the Geological Survey of Canada in conjunction with Ontario Ministry of Natural Resources (Ontario Geological Survey 1980a, 1980b; Friske, McCurdy and Cook 1990). The results of the current program will provide new regional geochemical data for both mineral exploration and environmental baseline purposes at a significantly higher resolution.

## REGIONAL SETTING

The project area lies within uplands of the James Region physiographic division of the Canadian Shield (Bostock 1970). Topography across the study area is largely bedrock controlled with the highest elevations (~480 m asl) corresponding to underlying Archean granitoid rocks. The northern half of the survey area, underlain dominantly by Archean granitoid rocks, features the highest elevations and is the most consistently rugged landscape. The southeastern portion of the study area, bordering Quetico Provincial Park, is also an upland area featuring gentle rolling hills composed mostly of Quetico Subprovince metasediments. Topography is generally much more subdued in the southern and southwestern portions of the survey area, with relief rarely exceeding 50 m.

The survey area straddles the boundary between rocks of the central Wabigoon and Quetico subprovinces. The general bedrock geology of this area is represented on the Ontario Geological Survey

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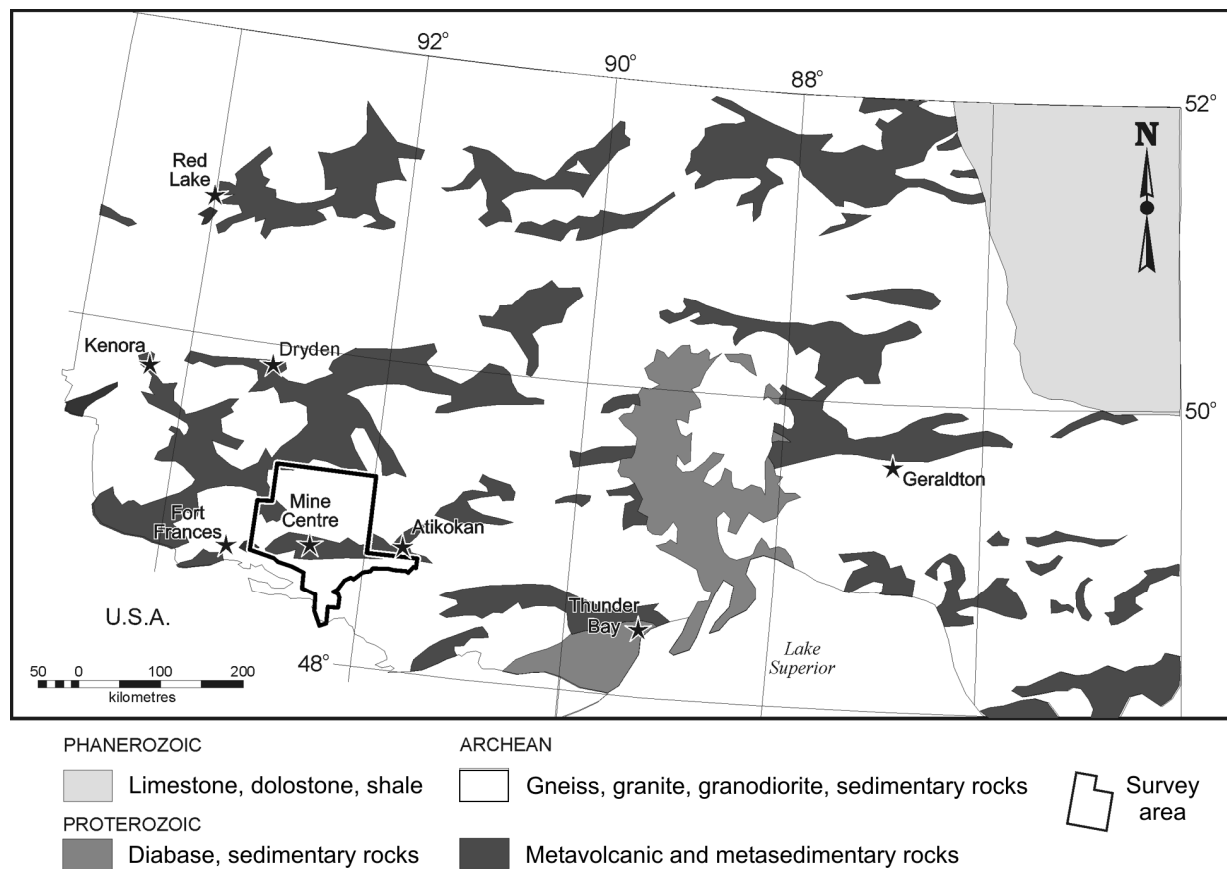
*Summary of Field Work and Other Activities 2009,  
Ontario Geological Survey, Open File Report 6240, p.28-1 to 28-5.*

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(OGS) 1:250 000 scale compilation map (Ontario Geological Survey 2006). The study area is bisected from east to west by the Fort Francis–Mine Centre and Calm Lake greenstone belts (Blackburn et al. 1991). Bedrock mapping of this region, at a scale of 1:50 000, was recently published by Stone (2008) and Stone et al. (2007a, 2007b). The Seine River fault marks the sharp transition to metasedimentary rocks of the Quetico Subprovince to the south, which extend to the border of the USA. North of the Fort Francis–Mine Centre–Calm Lake greenstone belts, the landscape is dominated by granitoid rocks; however, numerous thin slivers of volcanic greenstone rocks as well as discrete intermediate to mafic intrusions have been identified (Stone 2000; Stone and Hallé 1999; Ontario Geological Survey 2006).

Mineral exploration activity within the region has been focussed on the metavolcanic rocks, granitoid rocks and mafic intrusions that flank the trace of the Quetico and Seine River faults, which bisect the survey area from east to west. In particular, numerous gold showings are associated with quartz-filled ductile shear zones within granitoids that flank the Bad Vermillion Lake anorthosite intrusion (Blackburn and Janes 1983). Recent exploration activity has focussed on the iron-titanium-vanadium potential of the layered Bad Vermillion Lake anorthosite by Numax Resources Inc. (Bernatchez 2009) and diamond potential of the Grassy ultramafic pyroclastic intrusion (locally referred to as “GUP”) by MetalCORP Ltd.

Within the Quetico Subprovince metasediments, very little exploration activity has been documented; however, there is potential for copper-nickel-platinum group element (PGE) mineralization associated with “Quetico-type” mafic to ultramafic intrusions such as at Samuels Lake (Pettigrew, Hattori and Percival 2000). The northern half of the survey area has had limited exploration activity, mostly focussing on the Entwine intrusion (*see* Stone 2000) and the southern end of the Otukamamoan greenstone belt, near the northwest boundary of the survey area.



**Figure 28.1.** Location map of the 2009 Mine Centre lake sediment survey area.

No detailed Quaternary mapping coverage exists for the survey area; however, detailed investigations of the adjacent Fort Francis–Rainy River area have been completed by Bajc (2001). Regional compilations at a scale of 1:1 000 000, which include the Mine Centre study area, have been published (Barnett, Henry and Babuin 1991; Sado et al. 1995). These compilations, in part, have drawn upon several 1:100 000 scale engineering geology terrain maps for the region, which were published in 1980 (Mollard 1980; Roed 1980a, 1980b, 1980c, 1980d). These sources indicate that the most abundant surficial material within the survey area is a discontinuous sandy till. Areally extensive thick till units that completely obscure bedrock occur between Suckers Creek and Factor Lake (south of the Trans-Canada Highway), southwest of Otukamamoan Lake and west of Turtle River. Within the central core of the survey area (north of the Trans-Canada Highway, between the Big Turtle River and Little Turtle River), significant alluvium, glaciofluvial outwash and glaciolacustrine deposits are present. This ~400 km<sup>2</sup> area is also notable for a complete lack of lakes available for sampling. Alluvium and glaciofluvial outwash (sand and gravel) are present primarily within major valleys and present drainage spillways. Fine-grained glaciolacustrine sediments (clay) are present within Rainy Lake and the surrounding low-lying areas. The predominant and latest glacial-ice flow direction, based on glacial striae, was toward the southwest.

## **SAMPLING METHODS**

Organic-rich lake sediment samples were collected from a helicopter float using the OGS-designed gravity corer. Wherever possible, both shallow (0 to 15 cm) and deep (>15 cm) sediment samples were obtained at each sampling site. Based on average sediment rates of ~1.5 cm per decade within lakes on shield landscapes (e.g., Hunt 2003; Dickman and Fortescue 1991), the shallow sample is considered to represent sedimentation during the past ~100 years and, therefore, may be subject to anthropogenic contamination. The deep sediment sample represents sedimentation older than 100 years; therefore, this portion better reflects the effects of natural geochemical inputs that may be traced to local geology and/or mineralization.

Lake water samples were collected from a depth of 1.0 m using a weighted intake hose and pump. Water quality parameters, including pH and conductivity, were measured at each lake site using a flow cell attached to a multi-parameter probe. Lake water was pumped from each lake and allowed to purge the sampling system prior to the collection of a water sample and the recording of water quality parameters. Water samples were kept cool after collection and processed (filtered and acidified) within 6 hours of collection.

A global positioning system (GPS) receiver was utilized to record accurate sample site positions and to record each flight track. In addition, a GPS receiver connected to a tablet computer was utilized to provide “heads up” real-time navigation between lake sites.

## **SAMPLE PREPARATION AND ANALYTICAL METHODS**

Lake sediment samples were placed in breathable fabric bags and allowed to partially air dry prior to shipment to Sudbury. Final drying was done in ovens at a temperature of <35°C prior to partial pulverization in a ceramic ring and puck pulverizer and sieving to obtain the –60 mesh (<250 µm) size fraction. Laboratory analysis will include nitric acid–aqua regia digestion followed by inductively coupled plasma mass spectrometry (ICP–MS) to determine approximately 50 trace elements. Nitric acid–aqua regia digestion attacks all sample matrix constituents, except for silicate minerals and, therefore, is considered a nonselective, relatively strong partial extractant. Quality control will be monitored through the use of sample pulp duplicates and certified reference materials. Loss-on-ignition (LOI) is determined at 500°C, using an automated gravimetric technique. The deep (>15 cm) sediment samples will undergo further analysis for gold by instrumental neutron activation analysis (INAA).

Water samples were passed through 0.45 µm syringe filters and acidified to 1% ultrapure nitric acid within 6 hours of collection. Analysis of water will include direct aspiration ICP–MS to determine approximately 50 elements. Quality of the analyses is monitored through the use of sample duplicates, CANMET-certified reference standard SLRS-5 and distilled water blanks.

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# 29. Project Unit 08-010. Southern Ontario Stream-Sediment Geochemistry Survey

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## INTRODUCTION

The Ontario Geological Survey (OGS), in co-operation with the Ministry of the Environment (MOE) and the Ministry of Natural Resources (MNR), conducted a stream and river (herein referred as stream) sediment sampling survey in southern Ontario during 2008–2009 that covered an area of approximately 95 000 km<sup>2</sup>. Sampling occurred during the months of October to December 2008 and was conducted by 2 consulting firms, Conestoga-Rovers & Associates and XCG Consultants Ltd. Areas not sampled due to inaccessibility in the winter months were sampled by the OGS in June 2009. In total, samples were collected at 2289 sites (Figure 29.1) resulting in an average density of one sample per 41 km<sup>2</sup>.

## GENERAL BACKGROUND

Stream-sediment geochemistry is based on the principle that material on the stream bed represents a natural composite of all material entering the stream from the drainage catchment upstream of the sampling point. The results reflect the combined influence of geological sources (bedrock and glacial deposits), local surface conditions (soil type and vegetative cover) and man-made (anthropogenic) contamination, including airborne fallout. The OGS has previously completed 2 studies that can be considered orientation surveys that validated the applicability and relevance of performing stream-sediment geochemistry over southern Ontario landscapes (Fortescue 1984; Fortescue and Dyer 1994). The study reported by Fortescue (1984) was particularly comprehensive as it involved the collection and metals analysis of 4000 stream-sediment samples over an area of 20 000 km<sup>2</sup> in southern Ontario between Hamilton and London.

## OBJECTIVES

The primary objective of the present survey was to collect sediment for geochemical analysis to determine baseline and anthropogenic levels of organic and inorganic elements and/or compounds. The results of the survey have direct relevance in the assessment of the environmental health of watersheds, management practices and the establishment of stream sediment quality guidelines.

The results of the analysis will allow

1. the creation of an environmental geochemical baseline for southern Ontario which can be used in state of the environment reporting
2. the development of Ontario Typical Range Values

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*Summary of Field Work and Other Activities 2009,  
Ontario Geological Survey, Open File Report 6240, p.29-1 to 29-4.*

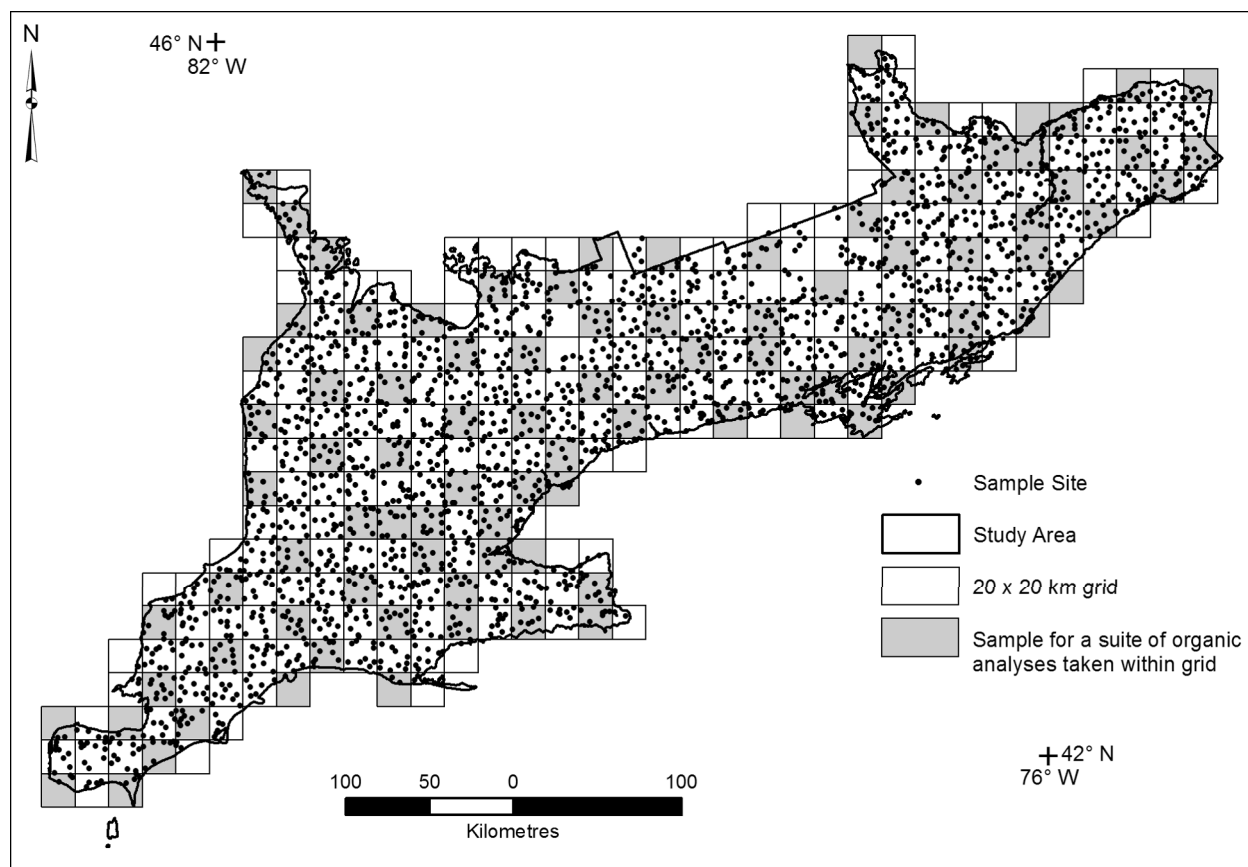
3. a broad-scale determination of the health of the environment as defined by the anthropogenic loading on the natural or baseline signature of stream sediments
4. a determination of the levels and distribution of persistent and newly emerging organic compounds in the environment

With this knowledge, effective watershed and land-use management plans can be developed that will protect the health of Ontario's population and the environment.

## SAMPLING METHODOLOGY

To ensure a relatively even distribution of sample sites an arbitrary 20 by 20 km grid was placed over southern Ontario (*see* Figure 29.1). A maximum of 10 stream sites were selected in each grid resulting in a sample density of about 10 samples per 400 km<sup>2</sup>. Lesser numbers of samples were collected in grids where a portion of the grid fell outside the study area or extended into a large water body (i.e., a Great Lake). Within a grid as many separate waterways as possible were sampled using standard MOE protocols. Where an active Provincial Water Quality Monitoring (PWQM) station was present within a grid, a sample was taken at that site.

At each site, a 500 mL sample was collected for inorganic analysis and a 200 mL sample was collected for organic analysis. Samples were collected at least 25 m upstream from any road or railway bridge and included only the top 10 cm of stream sediment (alluvial) material. The preferred sample



**Figure 29.1.** Southern Ontario stream-sediment survey sample sites. Shaded boxes indicate a grid from which a sample is being analyzed for a suite of organic compounds.

**Table 29.1.** Organic compounds to be determined and method of analysis.

	<b>Organic Compound</b>	<b>Method of Analysis</b>	<b>Detected Using</b>
1	Polychlorinated biphenyls (PCBs)	Gas chromatography	Electron capture
2	Organochlorine pesticides (OC Pesticides)	Gas chromatography	Electron capture
3	Polycyclic aromatic hydrocarbons (PAHs)	Gas chromatography	Mass spectrometry
4	Perfluoralkyl compounds (PFCs)	Liquid chromatography	Tandem mass spectrometry
5	Polybrominated diphenylethers (PBDEs)	Gas chromatography	High-resolution mass spectrometry
6	Polychlorinated dibenzo- <i>p</i> -dioxins (PCDDs)	Gas chromatography	High-resolution mass spectrometry
7	Polychlorinated dibenzofurans (PCDFs)	Gas chromatography	High-resolution mass spectrometry
8	Polychlorinated naphthalenes (PCNs)	Gas chromatography	High-resolution mass spectrometry
9	Dioxin-like PCBs (dlPCBs)	Gas chromatography	High-resolution mass spectrometry

medium was clay-silt rich material, but, if necessary due to the geological conditions, coarser material was collected. In order to ensure a representative sample from the site, material from a minimum of 3 locations per site was collected. The material was worked through a ½ inch sieve in the field, homogenized and excess water slowly decanted before placing in the 500 mL and 200 mL bottles. Upon collection, the 200 mL samples for organic analyses were kept chilled by being stored in coolers filled with ice. Within a day, the 200 mL samples were frozen to maintain the sample integrity until analyzed. The inorganic samples were kept chilled until preparation for analyses began.

## PRELIMINARY ANALYSIS AND OBSERVATIONS

### Organic Analyses of Samples

One hundred samples were forwarded to the MOE for a suite of organic analysis in February 2009. Half of the samples selected were located near large urban centres in southern Ontario and the remaining half were from rural areas. A research component of the project is the determination of the levels and distribution of persistent and newly emerging organic compounds in sediments of southern Ontario. As such, the project represents the first large-scale attempt to produce a modern “state-of-the-environment” report for this part of the province. Grids from which the samples were obtained are indicated by shading on Figure 29.1.

Because of the high cost of a full suite of organic analyses, the results obtained from the 100 samples will be considered in the determination of which analyses will be performed on the remaining samples. Depending on the results, and the resources available to the project in the future, analyses for certain compounds may not be performed on all samples.

A list of the organic compounds for which analyses are being conducted on the 100 samples and the type of analysis being employed are listed in Table 29.1. In all cases, the analyses involve a solvent extraction of the dried sediment, clean-up of the extracts to remove interfering substances and then subsequent instrumental analyses by 1) gas chromatography using high-resolution mass spectrometry; 2) gas chromatography–mass selective detector; 3) gas chromatography–electron capture detection; or 4) liquid chromatography with tandem mass spectrometry.

### Inorganic Analyses of Samples

Twenty samples for inorganic (metals) analysis have been submitted to the Geoscience Laboratories (Geo Labs) in Sudbury and the MOE laboratory in Toronto. Results from both laboratories will be compared to ensure inter-laboratory compatibility and comparison of results with samples previously collected across the province. The samples for inorganic analysis were selected from sites located near large urban centres where the companion sample is undergoing analysis for organic compounds.

**Table 29.2.** Inorganic elements to be determined.

Methods of Analysis: Aqua Regia Digestion (AR) followed by Inductively Coupled Plasma (ICP-) Mass Spectrometry (MS) or Optical Emission Spectroscopy (OES)								
Element	Detection Limit	Units	Element	Detection Limit	Units	Element	Detection Limit	Units
Ag	0.01	ppm	Gd	0.05	ppm	Sc	0.5	ppm
Al	100	ppm	Ge	0.1	ppm	Se	0.1	ppm
As	0.1	ppm	Hf	0.1	ppm	Sm	0.1	ppm
Au	2	ppb	Hg	0.01	ppm	Sn	0.2	ppm
B	1	ppm	Ho	0.01	ppm	Sr	0.2	ppm
Ba	0.2	ppm	K	0.01	%	Ta	0.05	ppm
Be	0.1	ppm	La	0.05	ppm	Tb	0.1	ppm
Bi	0.01	ppm	Li	0.5	ppm	Te	0.01	ppm
Ca	0.01	%	Lu	0.01	ppm	Th	0.1	ppm
Cd	0.01	ppm	Mg	0.01	%	Ti	0.01	%
Ce	0.03	ppm	Mn	5	ppm	Tl	0.02	ppm
Co	0.1	ppm	Mo	0.05	ppm	Tm	0.005	ppm
Cr	1	ppm	Na	0.001	%	U	0.05	ppm
Cs	0.01	ppm	Ni	0.2	ppm	V	1	ppm
Cu	0.2	ppm	P	10	ppm	W	0.5	ppm
Dy	0.05	ppm	Pb	0.2	ppm	Y	0.01	ppm
Er	0.01	ppm	Pr	0.05	ppm	Yb	0.1	ppm
Eu	0.1	ppm	Rb	0.1	ppm	Zn	2	ppm
Fe	0.01	%	Re	1	ppb	Zr	0.5	ppm
Ga	0.02	ppm	Sb	0.05	ppm			

These samples were dried, disaggregated and split by the Geo Labs; half of the prepped sample was shipped to the MOE laboratory for inorganic analysis, whereas the remaining half was retained in Sudbury for analysis. The samples are being analyzed for the elements listed in Table 29.2, as well as particle size analysis and loss-on-ignition (LOI) to determine, respectively, sample texture and percent organic matter.

## FUTURE WORK

Pending completion of the organic analysis being undertaken by the MOE laboratory, it is expected that a further 100 to 150 samples will be analyzed in the near future by a commercial laboratory. This component of the project is being undertaken in conjunction with Conservation Ontario (CO) and is being overseen by an OGS–MOE–CO steering committee. Results for this batch of samples are expected early in 2010. Further organic analyses will be completed as resources allow.

Geo Labs has begun the sample preparation for inorganic, grain size and LOI analysis on the remaining 2269 samples. It is expected that work on these samples will be completed in 2010.

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# 30. Project Unit 09-024. Shale Gas Assessment Project, Southern Ontario

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## INTRODUCTION

Over the next few decades, unconventional gas resource plays are expected to represent the main source of natural gas in the United States (Energy Information Administration 2009). One of the most promising of the unconventional gas plays is shale gas. Indeed, in the last few years, shale gas production has been increasing exponentially and reached over 1 trillion cubic feet (Tcf) in 2009, representing about 7% of annual natural gas production in the USA (Curtis 2009; Bustin et al. 2009). In Michigan, Ohio, Pennsylvania and New York, American states contiguous to Ontario, shale gas potential has been confirmed. Indeed, the Devonian Antrim, Ohio and Marcellus shales are now considered major natural gas resources in the USA. Also, in the province of Quebec, the potential resources of the Ordovician Utica shale have now been evaluated to exceed 50 Tcf (Lavoie et al. 2008). In Ontario, however, no potential shale gas units have been assessed. Therefore, the OGS has initiated a multi-year project intended to assess the shale gas potential in southern Ontario. This project will characterize various parameters of all prospective shale gas units.

## SHALE GAS ASSESSMENT

Shale gas can be characterized as gas plays for which the host rock acts as the source rock, the reservoir and the cap rock. The natural gas, usually produced *in-situ*, is found in fine-grained organic-rich reservoir rocks and is stored mainly in the sorbed state, predominantly on organic matter or also as free gas in the matrix or fracture porosity (Martini et al. 1998; Curtis 2002). Various parameters need to be defined in order to establish the potential of a shale gas unit including reservoir thickness, thermal maturity of organic matter, total organic carbon (TOC) content, type of gas generated (biogenic or thermogenic), adsorbed gas fraction, free gas fraction contained in primary and secondary porosity, and permeability. To define if a unit is economically viable, all factors must be described, rather than identifying threshold amounts or values of individual parameters. For example, shale with moderate organic content, but with a well-developed fracture pattern, is generally preferable to a gas-rich unit lacking permeability.

## POTENTIAL SHALE GAS UNITS IN SOUTHERN ONTARIO

Earlier work by Hamblin (2006) has identified a number of shale-rich units in southern Ontario that may have potential to produce shale gas. In southwestern Ontario, the Upper Ordovician Collingwood Member of the Lindsay Formation is defined as organic-rich interbedded calcareous shales and limestones that can reach 11 m in thickness (Russell and Telford 1983; Armstrong and Carter 2006). With

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TOC values up to 11%, this unit has previously been identified as a potential oil shale and as a source rock for oil found in Ontario (Powell et al. 1984; Churcher et al. 1991). It crops out and/or subcrops beneath a cover of glacial sediments over an area of about 200 by 200 km in south-central Ontario (Hamblin 2006).

The overlying unit, the Blue Mountain shale (Blue Mountain Formation), is described a grey-brown shale with thin, minor interbeds of limestone and siltstone and reached thickness of up to 60 m (Johnson et al. 1992; Armstrong and Carter 2006). At its base, it incorporates the Rouge River Member, a 2 to 15 m organic-rich interval (Hamblin 2006). The Blue Mountain Formation has TOC values of up to 9% and is thermally mature (Barker 1985; Obermajer 1997). In both the Collingwood Member and the Blue Mountain Formation, vertical fracture sets are well developed (Hamblin 2006). These Upper Ordovician shales are the equivalent of the Utica shale in Quebec, one of the most promising shale gas units in northeastern North America (Hamblin 2006; Thériault 2008).

In eastern Ontario, the Eastview Member of the Lindsay Formation is up to 10 m thick and comprises interbedded black shale and petroliferous limestone. This bedrock unit is the equivalent of the Collingwood Member found in southwestern Ontario (Williams 1991; Hamblin 1998). The overlying Billings Formation, consisting of up to 60 m of black shale with a few thin limestone beds (Williams 1991), is the stratigraphic equivalent to the Blue Mountain Formation. The few available thermal maturity and total organic content data indicate mature to overmature levels with a maximum organic content values of 2.7% for the Eastview Member and 4.2% for the Billings Formation (Legall, Barnes and Macqueen 1981; Barker 1985). In the Ottawa region, the major fracture patterns that are present may prove to be an important criteria in assessing shale gas potential (Hamblin 2006).

The black bituminous Marcellus shale (late Middle Devonian) is interbedded grey shale layers and fine carbonates (Musial 1982; Johnson et al. 1992). Limited in distribution to south of the Algonquin Arch, it does not crop out in southern Ontario. The unit reaches thicknesses of nearly 25 m and contains excellent organic-rich source rock intervals with TOC up to 4% indicating immature to mature levels (Obermajer 1997; Hamblin 2006).

The Upper Devonian Kettle Point Formation is the equivalent of the highly productive Antrim shale in the USA (Hamblin 2006). It consists of 65 m (maximum) of dark brown to black, organic-rich shale, silty shale and siltstone and subordinate organic-poor, grey-green silty shale and siltstone interbeds (Armstrong 1986; Armstrong and Carter 2006). It is thermally immature and reaches TOC values up to 15% (Obermajer 1997). As well, fractures sets are well developed and the presence of gas in water wells drilled into Kettle Point strata has been reported (Hamblin 2006).

Preliminary investigation indicates that other bedrock units in southern Ontario may possess shale gas potential. These units include the Shadow Lake, Blue Mountain, Carlsbad, Cabot Head and Rochester formations, as well as some shale-rich units in the Salina, Hamilton and Port Lambton groups. However, the first stages of the current project will focus on the most promising shale gas units as described above.

## **FUTURE WORK**

The main objective of the current project is to assess the potential of shale gas units by characterizing the various parameters noted above. Drill cuttings from 93 wells were sampled at the Ontario Oil, Gas & Salt Resources (OGSR) Library in July 2009. Also, in August 2009, a few outcrops in the Ottawa region were sampled. All samples have been sent to the organic geochemistry laboratory of the Geological Survey of Canada (GSC) in Calgary for Rock-Eval/TOC analyses. At the time of writing, results had not yet been obtained. Test values from previous studies (Legall, Barnes and Macqueen 1981; Barker 1985;

Armstrong 1986; Churcher et al. 1991; Obermajer 1997), along with the data from recent sampling and testing, will help produce TOC and maturation maps of the various shale units in southern Ontario. It should be then possible to establish the most favourable areas for shale gas drilling and testing. It is anticipated that initial target drilling and sampling will take place in 2010. During drilling, cores will be recovered and gas samples collected on which various tests will be performed. Tests will include analysis of the adsorbed and free gas fractions, evaluation of matrix and system permeabilities, estimation of primary and secondary porosities, and assessment of rock mechanics (Young modulus, Shear Bulk, Poisson's Ratio, etc.). Also, various geochemical and isotopic analyses will be carried out on gas samples.

## ACKNOWLEDGEMENTS

The assistance of Terry Carter (Ministry of Natural Resources (MNR)), Lee Fortner (MNR), Richard E. Ostrowski (OGSR), Jordan Clark (OGSR) and Cam McDougall during observation and sampling of cores and drilling cuttings in London was most appreciated. Also, the author would like to thank the GSC laboratory team in Calgary.

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# Metric Conversion Table

Conversion from SI to Imperial			Conversion from Imperial to SI		
<i>SI Unit</i>	<i>Multiplied by</i>	<i>Gives</i>	<i>Imperial Unit</i>	<i>Multiplied by</i>	<i>Gives</i>
<b>LENGTH</b>					
1 mm	0.039 37	inches	1 inch	<b>25.4</b>	mm
1 cm	0.393 70	inches	1 inch	<b>2.54</b>	cm
1 m	3.280 84	feet	1 foot	<b>0.304 8</b>	m
1 m	0.049 709	chains	1 chain	20.116 8	m
1 km	0.621 371	miles (statute)	1 mile (statute)	<b>1.609 344</b>	km
<b>AREA</b>					
1 cm <sup>2</sup>	0.155 0	square inches	1 square inch	<b>6.451 6</b>	cm <sup>2</sup>
1 m <sup>2</sup>	10.763 9	square feet	1 square foot	<b>0.092 903 04</b>	m <sup>2</sup>
1 km <sup>2</sup>	0.386 10	square miles	1 square mile	2.589 988	km <sup>2</sup>
1 ha	2.471 054	acres	1 acre	0.404 685 6	ha
<b>VOLUME</b>					
1 cm <sup>3</sup>	0.061 023	cubic inches	1 cubic inch	<b>16.387 064</b>	cm <sup>3</sup>
1 m <sup>3</sup>	35.314 7	cubic feet	1 cubic foot	0.028 316 85	m <sup>3</sup>
1 m <sup>3</sup>	1.307 951	cubic yards	1 cubic yard	0.764 554 86	m <sup>3</sup>
<b>CAPACITY</b>					
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	<b>4.546 090</b>	L
<b>MASS</b>					
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)	<b>31.103 476 8</b>	g
1 kg	2.204 622 6	pounds (avdp)	1 pound (avdp)	<b>0.453 592 37</b>	kg
1 kg	0.001 102 3	tons (short)	1 ton (short)	<b>907.184 74</b>	kg
1 t	1.102 311 3	tons (short)	1 ton (short)	<b>0.907 184 74</b>	t
1 kg	0.000 984 21	tons (long)	1 ton (long)	<b>1016.046 908 8</b>	kg
1 t	0.984 206 5	tons (long)	1 ton (long)	<b>1.016 046 90</b>	t
<b>CONCENTRATION</b>					
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

	<i>Multiplied by</i>	
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 which are 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 978-1-4435-1413-2 [print]**

**ISSN 1916-6117 [online]**  
**ISBN 978-1-4435-1414-9 [PDF]**